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The artificial leaf: An investigation into the sociotechnical integration of new solar energy innovations

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The Artificial Leaf:

An Investigation into the Sociotechnical Integration of New Solar Energy Innovations

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Accepted by the faculty of the Department of Integrated Science and Technology under the School of Integrated Sciences, James Madison University, in partial fulfillment of the requirements for the Honors College.

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PUBLIC PRESENTATION

This work was accepted for presentation, in part or in full, at the 11th Annual Society for the Studies of New and Emerging Technologies (S.NET) Conference in Quito, Ecuador on November 18-20, 2019, as well as the School of Integrated Sciences Senior Symposium at JMU on April 18, 2020. Unfortunately, both events were canceled.

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ABSTRACT

Increasing global demand, combined with the volatility of fossil fuels, has called for a large-scale increase in renewable energy production. Photovoltaics hold significant potential, but by nature, solar energy is intermittent and lacks dispatchability. Researchers around the world are working to create innovative solutions that utilize semiconductors found in solar cell technologies in new ways. This project harnesses photoelectrochemical water-splitting, which uses light energy to dissociate water molecules into hydrogen and oxygen. When the water-splitting device is submerged in saltwater and illuminated by sunlight, oxygen and hydrogen gas are produced on opposite surfaces, and can be either released or stored for later use. This device imitates the light-driven catalysts found in the chloroplasts of photosynthesizing plants, which is why it is so aptly named the artificial leaf. Stored hydrogen can be burned in a fuel cell, producing electricity with a byproduct of pure water and no greenhouse gas emissions. In the lab, two strategies to improve artificial leaves were investigated: (1) introducing a transparent, electrically-conducting scaffold made from textured SnO_2:Sb to support the $BiVO_4$ photocatalyst, and (2) applying a thin FeOOH co-catalyst coating to the $BiVO_4$ surface to enhance the efficiency of the water-splitting process.

While this product has not yet achieved optimum efficiency, experimental efforts are continuing to improve the performance of JMU artificial leaf prototypes. Once fully integrated into society, hydrogen produced from artificial leaves can be burned in small fuel cells within hydrogen-powered vehicles, while large-scale fuel cells can be used to provide both electricity and fresh water to island and coastal communities. Studying the artificial leaf as an emerging technology allows researchers to identify sociotechnical considerations through scenario crosses, the STIR protocol, systems dynamics modeling, and comparative analyses. Insights collected from experts in the field will inform project characteristics as design fictions are implemented. Existing policies, cultural views, stakeholder analyses, ethical key questions, local job/revenue creation, and the co-production of technology and society are each thoroughly explored to hypothesize how artificial leaves will be integrated into coastal communities.

Keywords: renewable energy, photovoltaics, hydrogen technology, Socio-technical Integration Research (STIR), design fiction, Science and Technology Studies (STS)

CHAPTER 1. PROJECT BACKGROUND

Sustainable technologies for producing energy and clean water are impending and vital in the coming decade. While nations such as the United States have not yet experienced harsh shortages of fresh water, many island communities have been depending on imported water for even simple tasks like bathing, cooking, and drinking. To sustain the population, mitigate troubling climate change pressures, and increase local prerogatives to switch to clean energy, it is imperative for island communities to take initiative in their production of both energy and potable water. This can be done through the research and development of the artificial leaf.

In 2011, Daniel Nocera and his fellow colleagues at the Massachusetts Institute of Technology (MIT) announced that they had successfully produced hydrogen fuel from only sunlight, carbon dioxide, and water using a cobalt-phosphorus alloy (Nocera, 2011). This breakthrough was exactly what the artificial leaf needed to gain momentum on an international scale. The industry defines artificial leaf technology as a "light-harvesting device, with self-assembled and auto-healing catalysts, that runs with solar energy, consuming water as food, splitting it, and releasing protons and electrons that can be used to make hydrogen or other renewable fuels for a sustainable future" (Joya et al., 2013). After the artificial photosynthesis process, the hydrogen is stored and burned in a fuel cell, which would create a byproduct of potable water for island locals in a sustainable manner (Chiavazzo et al., 2018). There is a niche in both the energy and desalination markets for artificial leaf technology, where coastal communities can invest in one technology and reap multiple benefits (Figure 1).

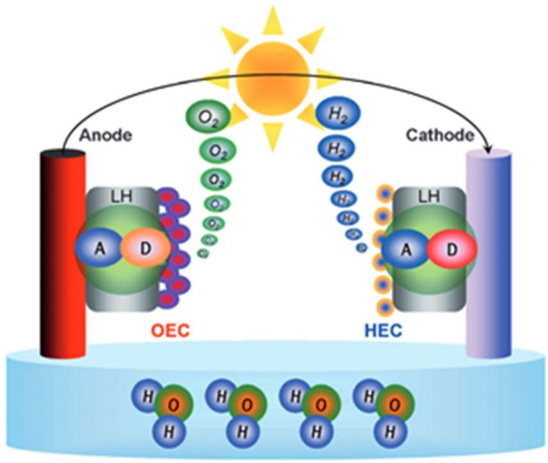


Figure 1. Artificial leaf using water and sunlight to produce hydrogen fuel (Joya et al., 2013).

While the idea of artificial photosynthesis has been examined for many years, current artificial leaf prototypes are not ready to be deployed due to low efficiencies, which is why very few researchers have begun investigating how this type of system may look in the future. There are many uncertainties surrounding the process, but one possible end goal would be to deploy groupings of artificial leaves in floating, raft-like structures along a coastline. From the perspective of the coastal natives, there would be very minimal visual impact because the artificial leaves would be submerged underwater.

CHAPTER 2. LONG-TERM HISTORY

When taking a long-term view of a problem, ISAT practitioners are able to employ a holistic perspective by accounting for a broader system within which the concept exists (Radziwill et al., 2012). By adopting a long-term perspective of artificial leaf development, one can better understand the history of its evolution, how certain variables might unfold in the future, and all of the dynamic forces at play.

2.1 The Global Energy Crisis

Due to the unsustainable and irresponsible use of fossil fuels globally, it is imperative that the world switches from nonrenewable to renewable resources. Currently, renewable energy technologies are used less than any other available energy (Figure 2). Nonrenewable fuels have taken hold of the economy while providing ease of access to energy worldwide. Because of significant investments in oil and natural gas, the transition to renewables presents many challenges. Some renewable energy sources are still more expensive, less efficient, and would take generous start-up fees to replace the existing systems. Gasoline and other common energy sources currently have strong infrastructure in place for transport via water, tankers, and gas station infrastructure. Another key advantage to fossil fuels is that they, in biogeochemical sense, contain concentrated solar energy because of their derivation from decomposed organic plant matter. Solar panels, on the other hand, can only process sunlight as a rate per unit of time. Because of this, it is important to utilize multiple technologies to capture and store these renewable resources, as well as implementing more incentives to conserve energy globally.

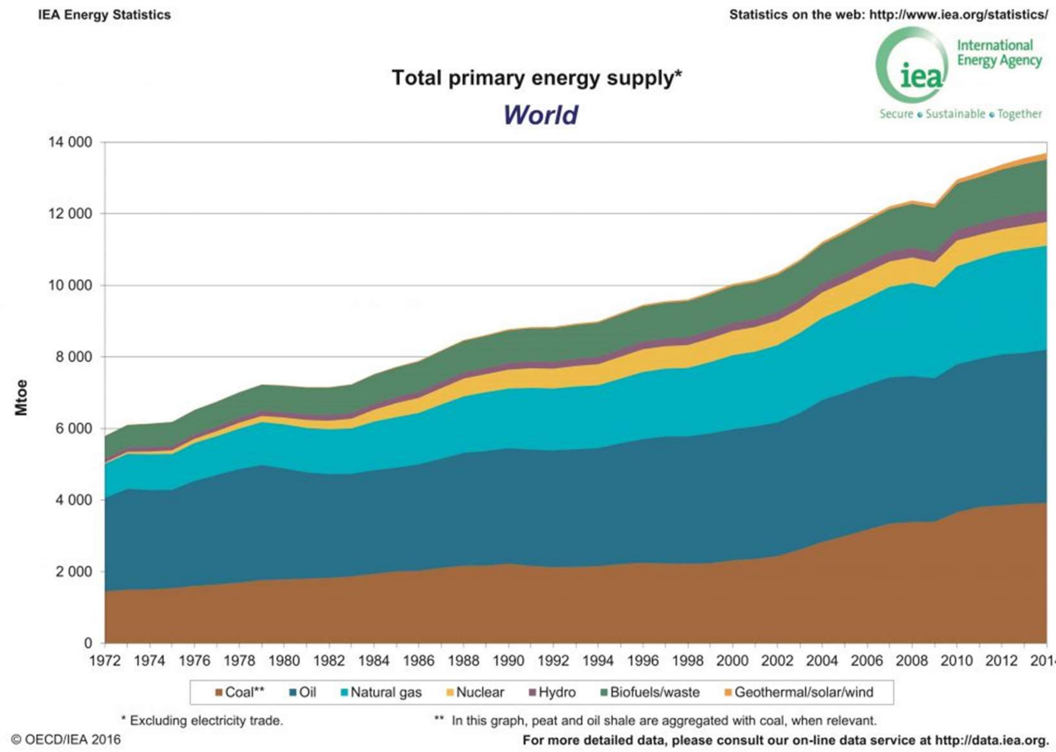


Figure 2. World total primary energy supply, by fuel (International Energy Agency, 2016).

Unfortunately, the countries most affected by the prevalence of greenhouse gasses, especially small coastal and island nations, contribute the least to the crisis. However, these nations are not only being encroached by rising tides, but commonly have tainted aquifers, unexpected weather patterns, and must spend thousands of dollars per year on import fees for their electricity, fuel, and water. In recognizing this, while it is important to view sustainable energy on a global scale, this project will focus more succinctly on developing ways to generate, store, and maintain small-scale photoelectrochemical cells that can be utilized in these coastal communities. Hydrogen produced by these photoelectrochemical cells can be burned in fuel cells to produce electricity and power personal vehicles, along with a byproduct of fresh water.

The need for renewable energy in island communities has been widely recognized, but the usable technologies will vary based on the geography. For example, onshore and offshore wind turbines have traditionally been used in the midwestern U.S. and Europe, where there are few Category 5 hurricanes. Severe weather such as this is quite common in the Caribbean and other parts of the world where most of the population resides in coastal areas, which is why large wind farms are not often found in these regions. Furthermore, countries with high levels of rainfall could deter solar energy from being effective. This is why countries like Jamaica have commissioned meteorologists to install automated weather data-collecting towers with sensors to determine the best energy technologies to be utilized in the future (Ashtine & Rogers, 2019). Because of these infrastructure and climate distinctions, it is imperative to consider the sociotechnical aspects of how artificial leaf technology could be implemented on a global scale.

With conventional photovoltaic energy, the most prominent downside is the intermittency of solar radiation. However, one advantage of artificial leaves is that they convert intermittent solar energy into storable hydrogen, functioning as an energy carrier so the hydrogen can be used even when the sunlight is unavailable (Lawrence, 2019). While the sun radiates constantly, weather patterns are constantly shifting, making it harder to achieve high efficiencies when capturing sunlight (especially in coastal regions). Conversely, fossil fuels are dispatchable, meaning the rate of the fuel's energy can be controlled by a combustion process. To mitigate this disadvantage, energy produced from solar radiation must be storable until it is needed to improve its reliability for consumers. Electrochemical batteries are the most common way to store solar energy; however, they come with several innate issues, such as hazardous mining of rare metals to create the battery, self-discharge concerns, and toxic disposal of the battery. A safer alternative to electrochemical batteries is converting solar energy to hydrogen gas by splitting water molecules and storing the hydrogen in a tank, as seen in artificial leaves (Figure 3).

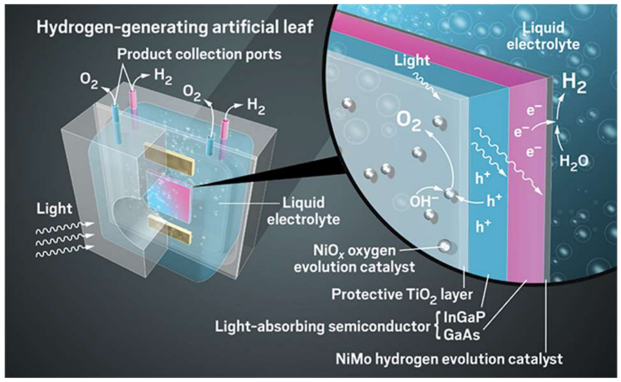


Figure 3. Illustration of the water-splitting process in artificial leaves (Bourzac, 2016).

At any time, the stored hydrogen can be recombined with atmospheric oxygen in a fuel cell to reclaim the energy it lost when the water split. Unlike traditional batteries, hydrogen fuel cells do not lose energy over time. As long as it is stored properly, hydrogen can be transferred in tanks and held until needed. Hydrogen is also much more environmentally-friendly than nonrenewable energy sources, and has the potential to transform many energy-intensive industries, such as transportation, as personal vehicles powered by hydrogen fuel cells enter the market.

Hydrogen energy has been around since the early 1800's, when streetlamps were powered by a hydrogen mixture, which inspired the invention of the first hydrogen fuel cell by Sir William Robert Grove in 1839 (The Environmental Literacy Council, 2015). Today, most hydrogen made by electrolysis for energy purposes is produced using electricity from fossil fuels like natural gas, coal, and nuclear energy. Hydrogen fuel can also be produced through steam methane reforming, which is a high-temperature process in which steam reacts with a hydrocarbon fuel to produce hydrogen. Occasionally, electricity from the grid will be used to produce hydrogen fuel as well. However, unless this is done during times of oversupply as a storage technique, this is quite inefficient because electricity that has already been produced is being pulled from the grid, and then must move through storage tanks and fuel cells just to become another form of energy. It is much more efficient to establish a direct line between the energy source and its end user with artificial leaf technology so the electricity in the grid can be used in applications that need it, such as powering homes and charging electric vehicles. Using renewable sources energy will always be the best alternative—and in this case, the only energy needed by the artificial leaf is from the sun, the most reliable energy supply in the universe.

2.2 Relevant Stakeholders

The artificial leaf has proven to be a multidisciplinary solution to the world's energy crisis. However, due to the high complexity of this project, it presents a large pool of stakeholders from across multiple industries. In an effort to better organize those involved in this solution, the Artificial Leaf Power Interest Matrix below ranks the relevant stakeholders from lowest interest and lowest power to highest interest and highest power (Table 1).

Table 1. Artificial Leaf Power Interest Matrix of stakeholders.

Low Interest & Low Power	**High Interest & Low Power**
Whoever controls the waters, boaters Water filtration companies Project maintenance workers Chemical and photovoltaic cell providers Grid managers	Current energy providers Environmental support groups Aquatic ecosystem, environment, atmosphere, etc. Island citizens, private and commercial consumers Research specialists and institutions
Low Interest & High Power	**High Interest & High Power**
Local island officials European Commission (funding) COVESTRO DOE and other legislative groups	Artificial leaf developers Utility companies and end-use distributors Hydrogen fuel cell manufacturers Project investors

The stakeholders with both the highest interest and power are the most important to artificial leaf development. First and foremost, when considering the implementation of artificial leaf technology into an island economy, the local citizens are highly involved. Not only are they likely to be the private consumers of the hydrogen energy, but they also live along the coastlines where the technology exists. Next, the people who are manufacturing and selling the artificial leaves are vital because without them, the development and construction phases would not be possible. They must monitor the supply and demand trends of the market—whether they are purchased by island economies or if private consumers are willing to invest in the technology. Additionally, the artificial leaf has the potential to create thousands of new jobs in the hydrogen fuel cell industry, whose job will completely depend on the success of the leaves. While working closely with utility companies and end-use distributors, these workers will ultimately be responsible for making sure the energy from the artificial leaves are properly stored, converted to usable energy, and then dispersed to energy consumers.

Next, there are some stakeholders that might have high interest but not as much power, or vice versa. Although they cannot speak up for themselves, which is why they have environmental support groups to speak for them, it is extremely important to consider the atmosphere, environment, and aquatic ecosystem all as relevant stakeholders. The environmental benefits of these technologies are endless; however, there are other important considerations, such as where the chemicals are sourced to construct the leaves, or whether the rafts of leaves will affect the health of the surrounding ecosystem. And as the artificial leaves become more widely used in society, they will likely become competitors of other renewable energy technologies within island economies—although they will all have similar sustainability goals.

On the other hand, there are several stakeholders that hold a great deal of power surrounding artificial leaves, yet do not have as much interest due to an abundance of responsibilities outside of this technology. For example, a major source of funding for artificial leaf research is the European Commission (E.C.), which has invested more than 8 million euros in the A-LEAF through the European Union's Horizon 2020 Research and Innovation Program ("An Artificial Leaf," n.d.). However, as they are such a massive organization, this is just one of many technological ventures that they are involved in. So, even though the development of the artificial leaves depends heavily upon E.C. involvement, they may not be as invested in the project as some of the more directly-involved stakeholders under high interest. Furthermore, COVESTRO is a German research company that produces many of the polymer materials used in artificial leaves ("A-LEAF," 2016). But for similar reasons, while artificial leaves depend heavily on the polymer materials provided by COVESTRO, they may not have a high interest.

Lastly, because this is such an interdisciplinary solution, there are many stakeholders that are still involved in artificial leaf development, even if they do not fall into one of these categories. Especially with the deployment of artificial leaves on rafts in coastal waters surrounding these island nations, anyone driving boats or regulating waterways must be aware of the technology. Then, once the energy is produced, the companies who are responsible for collecting the additional byproducts of clean water should be considered stakeholders as well.

CHAPTER 3. TECHNICAL COMPONENT

The goal of this investigation was to analyze the technical components of artificial leaf technology, which has the potential to provide renewable energy and clean water to island communities. The artificial leaf is based on a combination of both a photovoltaic and semiconductor-liquid junction approach to water splitting. These approaches consist of coupling a photovoltaic (PV) system with an electrolyzer into a single system where solar radiation illuminates the cells, providing electricity to facilitate water electrolysis (Currao, 2007).

The semiconductor-liquid junction approach involves splitting water along the boundary between the semiconductor and the liquid. One important material often used at this junction is bismuth vanadate ($BiVO_4$). $BiVO_4$ is a promising photoanode material used for the oxidation of water into oxygen gas (O_2) because it is scalable, inexpensive, and can produce films from a spray pyrolysis protocol that are monoclinic scheelite. This increases the electrode and electrolyte contact, and is hypothesized to increase photoelectrical performance.

3.1 Materials

Conducted in partnership with the JMU Center for Materials Science, the goal of this laboratory research was to develop an environmentally-friendly, water-splitting cell powered by solar energy and self-sustaining with the inflow of saltwater. By using a photoanode for photoelectrochemical water-splitting to produce storable hydrogen, this solar technology can be cost efficient and sustainable (Figure 4).

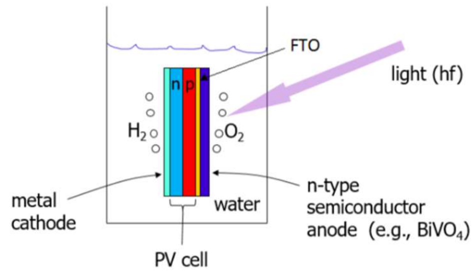


Figure 4. Artificial leaf diagram from previous JMU research (JMU Artificial Leaf Team, 2017).

All materials and resources necessary were provided in the Clean Room Lab at JMU.

3.2 Methods

There were two main objectives for the manufacturing process of this research. The first was to evaluate the approach of using textured antimony-doped tin oxide (t-ATO) as a transparent, conducting scaffold to support the $BiVO_4$--- photocatalyst material. The second was to test an iron oxyhydroxide (FeOOH) co-catalyst to improve photocatalytic $BiVO_4$ performance.

3.2.1 Ultrasonic Spray Pyrolysis

The most common and useful manufacturing process used by the JMU team was spray pyrolysis. Spray pyrolysis is a low-cost process employed to create thin film coatings on top of a substrate. In this process, the substrate was heated to approximately 400°C with a hot plate. An aqueous precursor solution of chemicals needed to make the coating was placed inside an apparatus that generated a fog of the solution with an ultrasonic transducer (vibrator). The fog was applied directly onto the substrate using a directed air gas flow. The heat from the hot plate caused chemicals in the fog to react on the surface of the substrate, producing the desired coating using a moving nozzle (Figure 5). The deposited layer thickness was dependent on time.

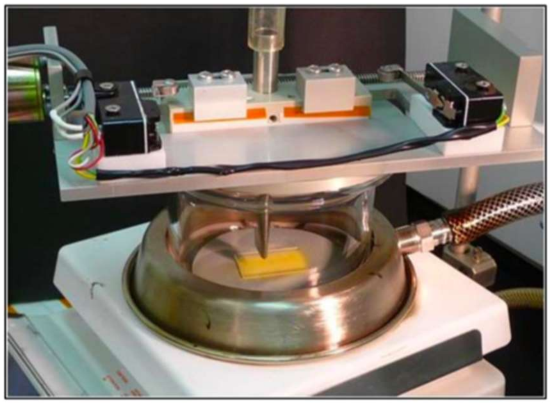


Figure 5. Spray pyrolysis machine applying the $BiVO_4$ layer (JMU Artificial Leaf Team, 2017).

Spray pyrolysis was used to deposit zinc oxide (ZnO) onto gallium arsenide phosphide (GaAsP), fluorine-doped tin oxide (FTO) onto the p-type surface of the GaAsP solar cells, and textured antimony-doped tin oxide (t-ATO) onto the FTO layer. (JMU Artificial Leaf Team, 2017). Until last year, the previous JMU Artificial Leaf Teams did not use t-ATO, as they used spray pyrolysis to deposit $BiVO_4$ directly onto the FTO layer instead.

3.2.2 Creating a Photovoltaic Cell

The heart of the artificial leaf is the photovoltaic (PV) cell. The PV material used for these artificial leaf prototypes was GaAsP. This material was selected because of its relatively high band gap, enabling it to produce approximately one volt when used in a PV cell. The leaves started with wafers of GaAsP, which are pre-doped n-type with tellurium. Cleanliness is vital for proper fabrication of PV cells, so the first step was to clean the GaAsP wafers with a mixture of sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2), and water. Then a second cleansing was done with hydrochloric acid (HCl) and water. Once the wafers were clean, ZnO was deposited onto the surface using spray pyrolysis. To accomplish this, a solution of zinc acetate ($ZnC_4H_6O_4$) was excited with an ultrasonic vibrator, creating a fog. The fog was then directed onto the substrate, which was heated to 430°C to induce a chemical reaction. On the surface of the GaAsP substrate, a layer of ZnO began to build. The thickness of the layer was visually estimated by observing the color of the leaf. The color changed as a function of the thickness because of the interference patterns associated with thin, transparent films during spray pyrolysis (Figure 6). Multiple samples were produced so different deposition conditions could be tested on various samples.

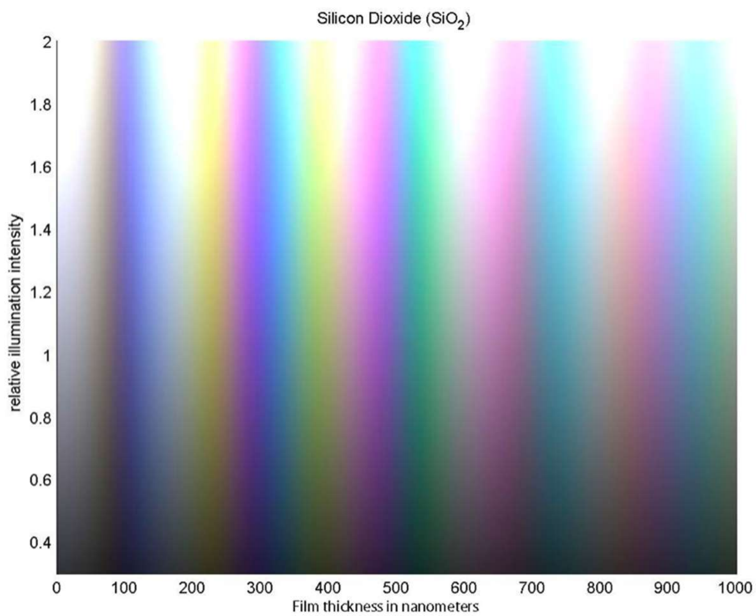


Figure 6. Oxide Film Color Chart to determine thickness of smooth ZnO layer (BYU, 2019).

After the leaves received their ZnO layer, they were annealed at 620°C for 83 minutes. This created the p-n junction, which generates the majority of the voltage and current in the leaf. When heated, Zn atoms from the ZnO diffuse into the GaAsP substrate. These atoms replace some of the Ga atoms near the substrate surface, producing “holes” and creating a p-type surface layer. These holes behave like positive charges, free to move through the crystalline $BiVO_4$ material. The resulting p-n junction pushes electrons through the PV cell after excess electrons are created in the GaAsP by the absorption of solar photons. This creates an electric current.

3.2.3 Fluorine-Doped Tin Oxide (SnO_2:F or FTO) Deposition and Textured Antimony-Doped Tin Oxide (t-SnO---$_2$:Sb or t-ATO) Deposition

These layers are deposited using spray pyrolysis. The starting mixture for FTO deposition was an aqueous solution of stannous chloride ($SnCl_2$) and ammonium fluoride (NH_4F) that was deposited on top of the solar cell. The desired thickness of the deposition was approximately 0.6 micrometers (μm). FTO is abrasion-resistant, transparent, and electrically-conductive. In terms of the complete leaf, FTO provides chemical protection to the GaAsP so it does not degrade over time, as $BiVO_4$ tends to be porous, allowing the saltwater to come in contact with the GaAsP. FTO also aids in moving the solar-generated electrons from the $BiVO_4$ to the solar cell.

Next, the textured tin oxide (t-SnO_2:Sb) was deposited by spray pyrolysis with a reciprocating nozzle moving back and forth. The starting chemicals were $SnCl_2$ and $SbCl_3$ dissolved in water. This was a 10-12 minute deposition at 450°C. Since both tin oxide layers are transparent, they allow sunlight transmission so it can be absorbed in the underlying solar cell, and the low sheet resistance creates a better conductivity. Textured tin oxide increases surface area since it allows more areas for the water to touch the surface.

3.2.4 Deposition of the Bismuth Vanadate ($BiVO_4$) Photoanode

The photoanode layer provides an additional voltage of approximately 0.2 volts (V) to the PV cell so electrolysis can be achieved. $BiVO_4$ was chosen for this layer primarily due to its complementary band gap to GaAsP, as well as the fact that it is earth-abundant, environmentally-benign, and relatively inexpensive. As this material absorbs wavelengths up to 520 nanometers (nm), it appears yellow in color (Figure 7).

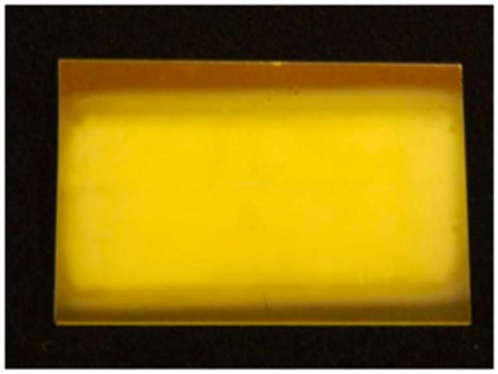


Figure 7. $BiVO_4$ photoanode deposited on glass sample (JMU Artificial Leaf Team, 2017).

The $BiVO_4$ photocatalyst was deposited on a 1.5” X 1.0” piece of glass. Wavelengths of light less than 520 nm are absorbed by this material, which excites some electrons (negative charges) out of their chemical bonds, making them free to move. The locations where the electrons used to be are effectively vacancies, called “holes”. The photocatalytic behavior of $BiVO_4$ is a result of the energy of the holes, making them able to rip electrons from water molecules (an oxidation process), breaking them apart. This produces oxygen atoms and hydrogen ions (H^+). Oxygen atoms then combine to form O_2 molecules, which leave the water as bubbles of O_2 gas. Meanwhile, a built-in electric field within the $BiVO_4$ pushes the electrons to the t-ATO and FTO layers. The PV cell can then take these electrons, boost their energy, and deliver them to a metal layer (e.g., platinum or nickel), which would either be on the back surface of the artificial leaf or a separate piece of metal foil immersed in the water for research testing purposes. At the metal surface, the electrons combine with H^+ ions to make hydrogen atoms, which then combine to create bubbles of H_2 gas.

In this research, $BiVO_4$ was deposited on top of the t-ATO layer by spin coating. A leaf sample was secured to the chuck of the spin coater. The starting material was an aqueous solution of ammonium vanadate (NH_4VO_3) and bismuth nitrate ($Bi(NO_3)_3$). A small amount of this clear-yellow solution was pipetted onto the sample surface and spun from 800 to 1200 rpm for several minutes to coat the t-ATO with a thin layer of the solution. Baking on a hot plate at 450°C caused a reaction between the NH_4VO_3 and $Bi(NO_3)_3$ that formed a thin $BiVO_4$ coating. Subsequent annealing in air at 500°C inside a furnace caused further crystallization of the $BiVO_4$ coating, forming the photocatalytically-active monoclinic scheelite crystal structure. The structure is shown below (Figure 8).

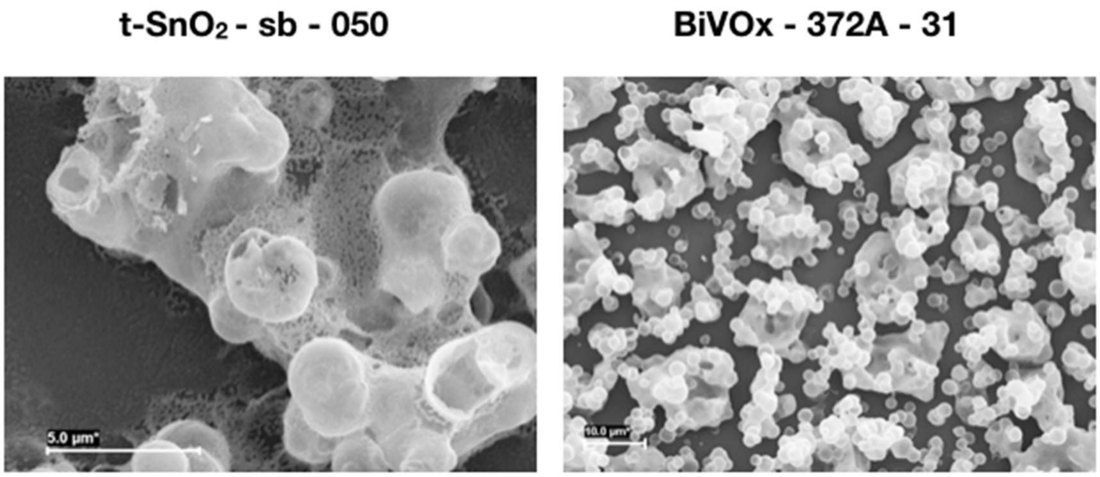


Figure 8. SEM images of textured ATO on FTO and ATO after $BiVo_4$ addition, respectively.

These images were taken under a Scanning Electron microscope. The image on the left shows spherical ATO particles that have agglomerated during the spray pyrolysis process to make the coating. The image on the right shows the textured ATO after it was further coated with BiVO4 by spin coating. They are not the samples that were used in the conclusion of this paper, but they help to identify the Bismuth Vanadate and Tin Oxide thickness which increases the area where the water can oxidize.

3.2.5 Chemical Bath Deposition of FeOOH Co-Catalyst

To further improve photocatalytic performance, FeOOH was added to select test samples to compare performance. This was done by placing the sample in a beaker of water solution and iron trichloride ($FeCl_3$), with a pH of 2.5, via a process known as hydrolysis (Figure 9).

Figure 9. FeOOH chemical bath deposition (Lawrence, 2020).

The water was then pulled apart to create the co-catalyst and HCl solution. FeOOH facilitates the removal of electrons from the water. This oxidizes the water, which breaks the water apart.

3.3 Performance Testing Procedures

Once the complete artificial leaf was synthesized, it was submerged in water, exposed to a solar simulator, and connected to a data acquisition system via its metal contacts (Figure 10). The solar simulator shined light at an irradiance of 1000 watts per square meter (W/m^2), the maximum normal surface irradiance at sea level on a clear day (University of Tennessee, n.d.). LabVIEW software tests that were programmed by a previous JMU student were used to directly measure both voltage generation and current production.

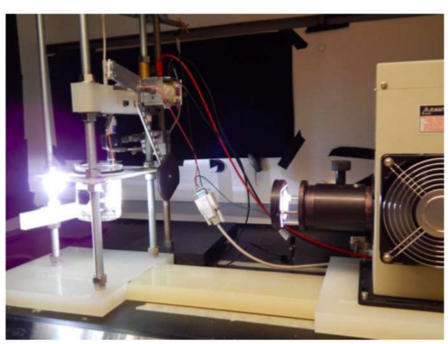


Figure 10. The instrumentation setup for testing the efficiency of the PV cells. This machinery simulates solar light in wavelength and amplitude (JMU Artificial Leaf Team, 2017).

The artificial leaf samples were first run under an open circuit voltage test. This test produces a graph of the generated voltage while the device is underwater and exposed to light. By running separate tests for the $BiVO_4$ photoanode layer and the complete leaf, researchers can observe the behavior of each component and how it contributes to electrolysis. This test can also help determine whether an entire leaf is capable of producing the 1.23 V necessary to split water.

Next, the samples underwent a linear photo-voltammetry (sweep) test. This test measures the flow of electrons in water while incrementally increasing the voltage across the leaf to determine the electric current. During both tests, a shutter covered the solar simulator lens every twenty seconds to ensure accountability and consistency in the data. Again, these tests were done to measure the performance of the $BiVO_4$ photoanode layer, as well as the entire leaf. With an applied voltage of 0 V, the current produced should be substantial enough to split water into H_2 and O_2 at an effective rate.

3.4 Experimental Results

The following results for test sample $BiVO_4$-387 detail the current density, in units of milliampere per square centimeter (mA/cm^2), generated by the test sample as the supplied external voltage was swept from -0.5 V to +0.5 V (Figure 11-12). When viewing the following graphs, it is important to note the current density generated at 0 V. At this voltage, the sample did not receive any external voltage from the power supply. Instead, it was using only the voltage generated at either the water-splitting boundary, the solar cell, or both, to generate current.

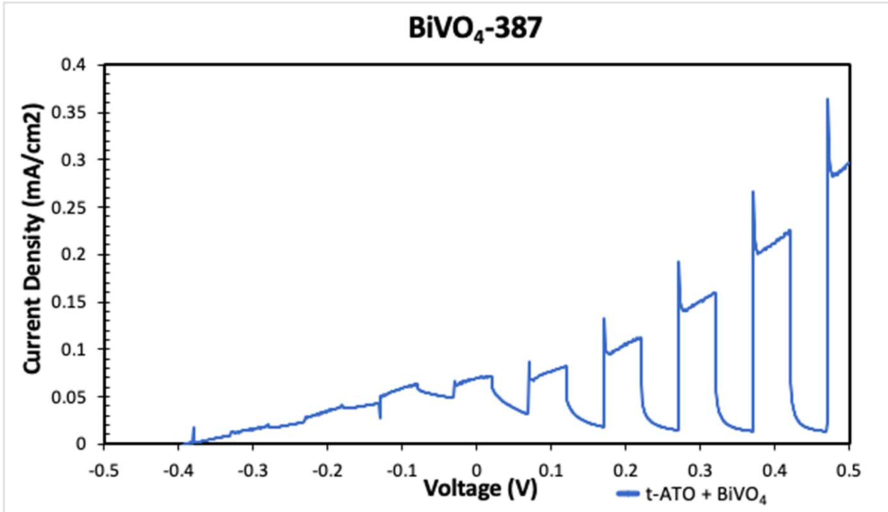


Figure 11. Current density generated by only the $BiVO_4$-water junction as voltage was swept from -0.5 V to +0.5 V.

Current density is simply defined as the amount of current generated by the area of the test sample. This sample featured the $BiVO_4$ layer deposited via the spin coating process, which served as a thin shell over the t-ATO scaffold.

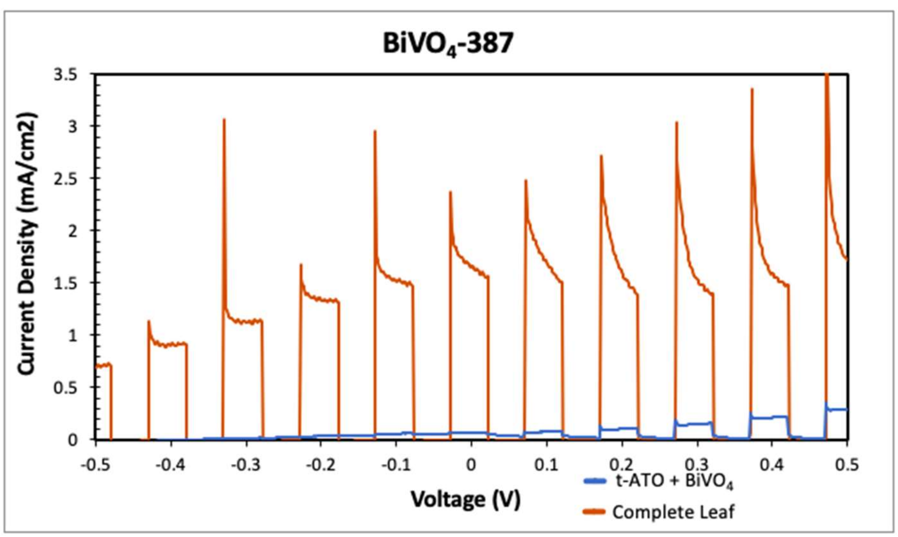


Figure 12. Current density generated by entire artificial leaf sample comparison as voltage was swept from -0.5 V to +0.5 V.

In Figure 12 above, the orange line shows the current density generated by the entire artificial leaf immersed in water as voltage. The blue line shows the current density generated by the $BiVO_4$ - water junction alone, shown in Figure 11. Completing the leaf greatly increases the current density.

In the final graph below, the performance of sample $BiVO_x$ - 131A is shown before and after co-catalyst addition, while the performance of sample $BiVO_x$ - 131B is shown only after co-catalyst addition (Figure 13). In these samples, the FTO layer was applied just like the other samples. However, there was no textured ATO present because the $BiVO_4$ was directly deposited on the FTO.

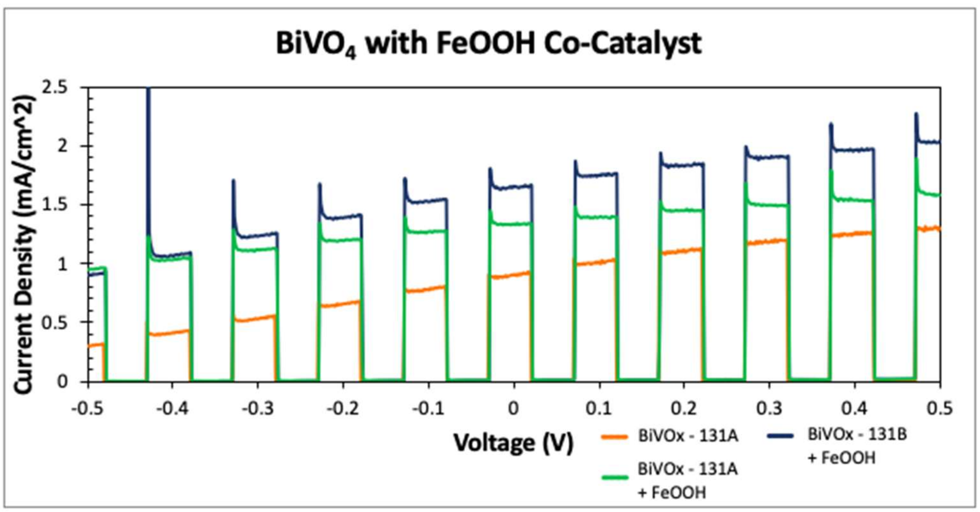


Figure 13. Current density generated by the complete artificial leaf immersed in water, with and without the added co-catalyst FeOOH as voltage was swept from -0.5 V to +0.5 V.

Over time, it was discovered that the FeOOH co-catalyst improves the performance of the $BiVO_4$ layer added by spray pyrolysis. However, it does not improve the performance of the $BiVO_4$ layer added by spin coating. It is not yet understood why these two processes affect the performance of the co-catalyst differently.

CHAPTER 4. SOCIAL CONTEXT COMPONENT

While the technical component of this report was vital in increasing the efficiency of artificial leaf prototypes at JMU, there is much more to this research than simply the laboratory exercise. No matter how efficient artificial leaves become as research continues to improve, it will be impossible to integrate this emerging technology without analyzing its socio-technical considerations. The goal of this in-depth analysis was to create a collection of scenarios, based on these criteria, to explore deployment of artificial leaves in different geographic contexts and to examine the accompanying societal and ethical dimensions.

4.1 Defining the Methodology

The following methods aim to justify why a comparative analysis of three economically- and socially-differing island communities was conducted to study the integration of artificial leaf technology. Island communities were considered the primary focus in this analysis, with an end goal of minimizing the disruption of day-to-day life amongst locals. Island communities are surrounded by large bodies of saltwater, which is where the rafts of artificial leaves would be placed. Island communities also benefit greatly from reducing imports for gas, electricity, and fresh water, which decreases their dependence on other countries while saving them money. Because of the smaller size of these coastal communities, this technology could likely sustain groupings of small villages, whereas this technology would not prove to be as efficient for larger communities further inland. Island communities were chosen to set a standard for the best potential location to deploy artificial leaf technology; however, the goal is to produce a technology that can one day be effective for all types of coastal communities.

These methods include the collection and validation of data, the cultural ideologies that may influence the way emerging technologies are adapted and integrated into communities, the political hierarchy in selecting alternative types of fuel, and the deep-seated social assumptions of renewable energies (Jasanoff, 2007). This investigation followed a modified combination of the methods outlined by Sheila Jasanoff, author of *Designs on Nature*, and Woody Wade, author of *Scenario Planning: A field guide to the future.* The methods are as follows:

1. Framing the problem
2. Gathering information
3. Identifying driving forces
4. Defining the future's critical uncertainties
5. Generating scenarios
6. Validating scenarios and identifying further research
7. Assessing scenario implications and defining possible responses
8. Monitoring and updating scenarios

While this is not a one-size-fits-all approach, these steps are to be taken as planning and workshop ideas throughout the project to enhance socio-imaginary output (Wade, 2012).

4.2 Framing the Problem and Gathering Information

By examining the potential political, economic, cultural, ethical, environmental, and societal implications of artificial leaf technology, project developers can make efforts to mitigate concerns based on the individual locations. While each of these categories will vary based on the region, generally speaking, the driving forces surrounding artificial leaf development in any area will closely resemble the following analysis.

4.2.1 Political and Economic Considerations

Artificial leaves are an emerging technology with a wide range of applications; but, its geopolitical and economic dimensions are nebulous, primarily due to its newness. However, there are a breadth of policies regarding renewable energy technologies and clean water initiatives that can support artificial leaf development, such as research programs, budget proposals, and goals to devolve from fossil fuels.

There are many economic impacts of artificial leaf development, both positive and negative. By creating hydrogen fuel locally, island and coastal economies no longer have to depend on imported energy, which would save them money to put towards other economic needs, such as transportation, infrastructure, and local businesses. Having the ability to produce clean water locally also has very similar benefits, and can push these communities towards independence with locally-sourced water and energy. Recognizing this energy transition strongly correlates with the UN General Assembly Agenda for Sustainable Development, specifically SDG7, which aspires to “ensure access to affordable, reliable, sustainable, and modern energy for all” (Calzadilla & Mauger, 2018). On the other hand, when considering the development of artificial leaf projects, there are two major drawbacks to be considered: the cost (floating systems may be more expensive to construct than regular ground-mounted solar panels) and maintenance (it is much harder to control floating systems, and unexpected weather events could cause serious damage). There are also some negative socio-economic impacts that must be considered alongside these benefits, such as the effect of artificial leaf deployment on navigation, fishing, and tourism. Especially since many coastal economies are built on fishing and tourism, serving as sources of income for many, it is imperative that developers site artificial leaf rafts with these considerations as a top priority.

When predicting the challenges that artificial leaf developers may face during the deployment of a project, one must look to the political and economic spheres surrounding other emerging technologies with similar characteristics. For example, floating solar photovoltaic systems are a technology currently on the market that closely resemble artificial leaves. According to NREL, floating PV systems represent solar PV systems that are being sited directly onto bodies of water (Aznar et al., 2019). Currently, the primary market for these systems includes the U.S. and Japan, with an emerging interest across Southeast Asia, Europe, and the Middle East; however, there are still no specific regulations on the permitting and licensing of floating PV systems in any of these regions. For now, these procedures have been assumed to be the same as ground-mounted PV, but the industry predicts that this will change as floating PV systems become more popular (World Bank Group et al., 2018). Financial incentives, such as feed-in tariffs and extra bonuses for RECs, as well as supportive governmental policies, such as ambitious energy targets and openness amongst regulatory entities who control the bodies of water, have both been the most vital when considering the political and economic scope of this technology. Specific interest in floating PV systems has grown because of competing land-use pressures, renewable energy and energy security goals, and power sector resilience motivations. While many of these benefits are similar to those of artificial leaves, the major difference between these two technologies is that floating PV systems are most often sited on calm lakes and reservoirs, while artificial leaves will be deployed in the ocean along shorelines.

Once the artificial leaves are constructed in such a way that the hydrogen can be collected and burned in a fuel cell, the next obstacle is to determine how this new energy source can be used within the local community. Hydrogen has potential in all energy sectors: transportation, commercial, industrial, residential, and even energy storage. Hydrogen has been typically burned in fuel cells to generate electricity, but according to the U.S. Office of Energy Efficiency and Renewable Energy, it is also commonly used in petroleum refining and fertilizer production, while transportation and utilities are both emerging markets ("Hydrogen," 2017). Applications include distributed or combined-heat-and-power, backup power, systems for storing and enabling renewable energy, portable power, auxiliary power units (for trucks, aircraft, rail, and ships), and specialty vehicles (such as forklifts, passenger and freight vehicles, cars, trucks, buses, and even space shuttles). On April 9th, 2019, Sen. Peters, Gary C. (D-MI) introduced the "Vehicle Innovation Act of 2019" to the U.S. Senate Committee on Energy and Natural Resources. This bill was proposed in an effort to encourage the D.O.E. to "conduct a program on materials, technologies, and processes with the potential to substantially reduce or eliminate petroleum use and the emissions of U.S. passenger and commercial vehicles, including in the areas of natural gas and hydrogen vehicle technologies" (Peters, 2019). After addressing the health and safety concerns associated with hydrogen energy production, perfecting collection and distribution methods, and passing the appropriate legislation, it has endless applications throughout society.

Out of all the countries in the world, the highest importers of bottled water per capita are arid countries and small island nations (Deschenes & Chertow, 2004). And up to this point, many of these areas have turned to desalination, which is a highly expensive and energy-intensive process. Ever since Malta built one of the first desalination plants in the world, they have proven that they are taking the idea of localized clean water production very seriously (Macedonio et al., 2012). Then, in 1998, the European Union (EU) adopted the Drinking Water Directive to encourage small island nations like Malta to get citizens involved in finding creative ways to provide clean water while streamlining legislation (Kaika, 2003). These countries, who have been forced to pursue innovative solutions in the past, are now fortunate enough to be surrounded by saltwater that can simultaneously be used to generate energy and create a byproduct of fresh water, all while saving them money, with artificial leaf technology. This potable water can then be collected and sold within the country's borders or exported, which would support the local economy rather than having to import endless shipments of bottled water. From an ethical and social justice perspective, everyone in a moral economy deserves access to clean water, as it is a basic human need and should be treated as an innate right. Artificial leaf researchers hope to bring this technology to small island nations that need it most, for both the purposes of energy generation and clean water, and that the locals will welcome the idea with open arms amidst an economic and cultural shift towards more sustainable solutions.

When adopting new technologies, communities are often skeptical of scientists and contractors, assuming monetary rewards may take precedence over community ease and health. Desirable commodities show how policies can be shaped not only by economic structure, but also by the surrounding cultural system. According to Homer Neal, author of Beyond Sputnik, modern science "transcends global boundaries," and does so by "homogenization" of global culture (Neal et al., 2008). As solar energy research grows in popularity around the world, each nation is watching the next to configure the most effective political framework that will encourage future renewable energy development without sacrificing their economic structure. The policies themselves will have cultural underpinnings, such as whether the community supports each other in developing and maintaining the technology, or if it is the responsibility of an outside third party. There are several essential questions here that must be addressed: (1) what new jobs will be made available if the artificial leaf is made commercially available?, (2) what needs to be done to mitigate concerns amongst locals?, and (3) how are the EPA and other environmental departments going to test the environmental effect of these contractions? If new jobs are created when artificial leaves are deployed within a coastal community, they could be both white and blue-collar, but many different stakeholders are involved. For example, the surrounding community may be unhappy if they do not receive maximum benefits from the project being franchised or non-locals traveling to the coastal community to fill an overabundance of white-collar jobs. It would be more helpful to craft maintenance and testing jobs specifically for locals, or to hire locals for positions that mirror those in the oil and gas industries, such as trucking, delivery, inspection of parts, audits, and cleaning.

While current policies and economic structures do not specifically address artificial leaf development, these policies should be introduced in small steps, rather than all at once. Regardless of what these regulations may look like in the future, this is primarily due to the highly complex nature of the technology. As proposed by Charles E. Lindblom in his publication entitled “The Science of ‘Muddling Through’,” incrementalism is a valuable tool when considering the best way to introduce policies related to new technologies (Lindblom, 1959).

4.2.2 Cultural Dynamics and Ethical Dimensions

In addition to the numerous policies related to the artificial leaf, there are also a variety of cultural dynamics and ethical dimensions involved in the development of new technological innovations. For example, every time a work of science fiction assigns a negative connotation to a new emerging technology, they are sharing this perspective and planting a seed of fear across society. However, with the research that has been done on artificial photosynthesis, there is already a far more accepting community who understands the process of photosynthesis in plants, and can imagine how it can be utilized to generate energy in a renewable fashion. In the book Weight of Light: A Collection of Solar Futures, there are many positive connotations regarding the future of solar power, and even discusses how citizens may rearrange their lives, values, and relationships based on the integrations of these innovative PV technologies (Eschrich & Miller, 2018). As mentioned in the book, an event hosted by ASU's Center for Science and the Imagination focused on the following variables when analyzing the potential of various solar technologies: geography, size, aesthetics, efficient versus abundant deployment, extraction and supply chains, ownership and governance, storage, waste, and recycling. These same variables are highly relevant when studying the sociotechnical considerations of artificial leaf technology.

When studying established economies, it is common to find what many call "legacy technologies," where the community has built so much infrastructure around a particular technology that it is extremely difficult to move towards new solutions. However, in areas that are less developed, the artificial leaf and other emerging technologies may not face as much opposition if the infrastructure is not already in place to generate the fuel, electricity, and clean water that could be produced by the artificial leaves. Therefore, there is a niche in the renewable energy generation market for artificial leaves in these smaller, developing economies that are beginning to turn towards alternative energy sources. Additionally, with the consumer's preferences in mind, researchers are currently searching for the most efficient prototypes that require the least amount of space and are produced using sustainable methods and materials, which may otherwise cause local pushback. Less obstruction of the space surrounding the energy generation site by the artificial leaves, both in the water and along the coastline, will result in a greater likelihood of community acceptance. In today's renewable energy market, there are no direct competitors of artificial leaf technology that create hydrogen energy from water molecules and solar radiation—however, there are some floating solar PV farms currently in development, which are not yet a mainstream technology. Instead, the two primary competitors of artificial leaf technology that generate energy in oceans include offshore wind farms and wave energy converters. Although these are two successful renewable technologies used around the world, they both take up a larger geographic area than the proposed artificial leaf rafts, and may have negative environmental impacts when tethered to the ocean floor.

While the current literature confirms that an artificial leaf has no direct environmental consequences during its active lifetime, there is still an anticipated pushback against the concept of floating devices along coastlines for energy generation. The social impact on fishing communities is predicted to be an important factor, as the artificial leaves could interrupt fishing waters and darken the water beneath the rafts, deterring fish from swimming underneath. This could potentially have a negative effect on the local economy, as fishermen often flock to coastal communities for their business. In general, the coastal environment tends to be a major tenet of the culture amongst island natives. So, the artificial leaf industry must be extraordinarily careful when it comes to advising natives how they can turn the sunlight and ocean surrounding their home into a source of renewable energy and clean water. One of the islands being considered for the deployment of artificial leaf technology is the nation of Malta, where researchers at the University of Malta have thoroughly investigated the idea of "genius loci," which is more commonly known as "sense of place" (Ebejer, 2014). Specifically within an island community like Malta, the locals have developed special connections to the natural world around them because they learn from such an early age how important it is to protect the land on which they live. This love for the environment has been passed down for generations, and for many, protecting their home means a great deal to them. So, as artificial leaf developers create a technology that could be subtle and have little environmental impact, all while producing clean energy and fresh water, they predict it would take these island natives and their forward-thinking mindset to get this project off the ground and into the sea. However, the evidence supporting artificial leaves must be framed correctly to appeal to the "sense of place" amongst locals.

With the emerging threat of climate change, many island natives are in danger of losing their homes as sea levels rise. This is why artificial leaf developers must first educate the locals why this solution could help slow, or even negate, the rising sea levels. From Tangier Island, Virginia, all the way to Fiji, there are thousands of islands threatened by climate change, and there is little being done about it. As a preventative measure, the first American climate refugees were relocated to higher ground in Louisiana by the U.S. government when they had no choice but to leave their native island that was slowly creeping into the Gulf of Mexico ("Isle De Jean Charles Resettlement Project," 2018). When considering the high price tag that was associated with this relocation, the U.S. government should actively seek solutions to this crisis, such as the artificial leaf, in order to avoid being obligated to relocate more U.S. citizens. There are many islands all over the world just like Isle De Jean Charles; however, artificial leaf developers hope that this solution will provide these nations with the technology they need to generate their own electricity, while also inspiring hope within the coastal communities as locals are encouraged to do their part to protect their home and other islands across the globe.

4.2.3 Environmental Assessment

When it comes to emerging renewable energy technologies used to combat global climate change, the goal is to ensure that there is a net positive impact on the environment once the technology is deployed (including extraction of materials, manufacturing processes, construction, etc.). For artificial leaves, most of the materials required can be sourced locally and/or sustainably, and the manufacturing and construction processes seem to be less energy-intensive compared to other renewable energy technologies.

There are numerous environmental benefits associated with floating rafts of artificial leaves. First of all, the ocean space used for the rafts will replace the miles of agricultural land being consumed by major solar developers—and as the world population continues to rise, the agricultural industry will not be able to sacrifice this land for energy development as they try to compensate for increasing food demand. Additionally, the artificial leaf rafts will reduce the underwater sunlight exposure, which can mitigate the problem of algae growth, which is often harmful to marine life (Aznar, 2019). Developers must be cautious, however, to ensure that they achieve a balance between preventing excess algae growth without cutting off solar radiation from phototrophic organisms. The impact of the reduction of UV rays on ocean environments is yet to be fully understood, especially in the case of artificial leaf deployment.

There are also benefits associated with the relationship between the rafts and the surrounding body of water. The artificial leaves may reduce evaporation, for example, which is a growing concern in many warm and dry geographical areas where artificial leaf deployment is being considered. And it is predicted that global climate change is predicted to make dry areas even drier, making this an increasingly severe problem. Also, the water surrounding a floating solar panel cools the panel, thus increasing its efficiency, so it is possible the water could have the same effect on artificial leaves. This is why researchers have already found that these floating solar panels produce more electricity than a similar ground-based solar panel (Blackwood, 2014). However, this relationship is two-fold, because while the artificial leaves may benefit from the water cooling, there is a risk of the rafts increasing the temperature of the water during the water-splitting process. Despite these serious environmental concerns, researchers predict that floating systems will not cover a large enough area to disrupt entire marine ecosystems.

When compared to other renewable energy technologies found in the ocean, not only would artificial leaf rafts have a smaller visual impact and be more aesthetic to locals, but they would also have less of a structural impact on the aquatic ecosystem because they do not reach the ocean floor, unlike most offshore wind turbines and wave energy converters. The aesthetics associated with floating solar development is something that Ocean Sun, a solar energy company from Norway, has taken very seriously. They developed its floating solar technology based on biomimicry—a method of finding solutions to human problems by observing and imitating natural, biological systems. In this case, Ocean Sun based its technology on the giant water lily, a flower native to the Amazon River basin (Figure 14).

Figure 14. New floating solar "lily pad" (left) was inspired by the giant water lily native to the Amazon River basin (right) to reduce overall environmental impact (Ocean Sun, n.d.).

Similar to these floating solar panels, artificial leaf developers have employed biomimicry to imitate the light-driven catalysts found in the chloroplasts of photosynthesizing plants. While natural photosynthesis reactions produce glucose and oxygen, artificial leaves produce hydrogen and oxygen. And as the hydrogen is transported back to shore to be stored and burned in a fuel cell, O_2 gas bubbles are released underwater from the surface of the artificial leaves. The oxygen produced from this process can possibly be stored alongside the hydrogen and sold to fulfill industrial and medical applications. In industry, oxygen can be used for steelmaking, metal refining and fabrication processes, and environmental protection in treatment plants and facilities. It can also be used in various medical applications—from first aid to respiratory treatment. If not, the oxygen would simply be released into the atmosphere above the surface of the water. This may also have a potential impact on the dissolved oxygen (DO) in water, which is a measure of how much oxygen is dissolved in the water and is available to living aquatic organisms. According to the National Oceanic and Atmospheric Administration, oxygen can naturally enter the water by one of two ways: (1) diffusion from the atmosphere, or (2) photosynthesis in aquatic plants (NOAA, 2020). However, artificial leaf development on a global scale would potentially create a new, third method of DO production. DO is an important determinant of water quality, with surface water average annual concentrations in oceans ranging from 9 mg/L near the poles to 4 mg/L near the equator (USGS, n.d.). Lower DO concentrations are found near the equator due to higher salinity, which corresponds with regions of higher solar radiation ideal for artificial leaf development, therefore presenting new challenges when trying to protect the system from saltwater corrosion. Identifying these regions of increased solar radiation heavily influenced the selection of the three potential sites for artificial leaf deployment analyzed in this research, including Haiti, Hawaii, and Malta, which are all found within 2,500 miles of the equator.

There are also environmental impacts that must be considered once the hydrogen is collected from the artificial leaf rafts. The primary concern when constructing storage tanks for hydrogen gas is flammability (Figure 15).

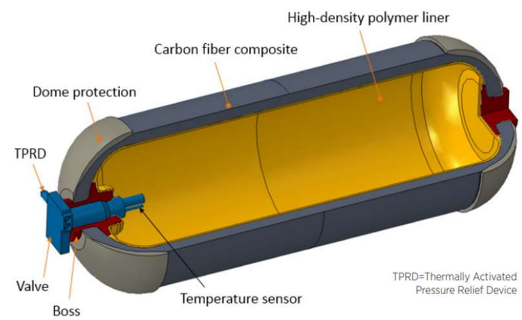


Figure 15. Schematic of a Type-IV Composite Overwrapped Pressure Vessel (COPV) designed for small-scale compressed hydrogen storage (Fuel Cell Technologies Office, 2017).

So, once it is transported and stored onshore, the compressed hydrogen must be collected in a fire-resistant storage tank between 350-700 bar (5,000-10,000 psi). Proper fire-prevention procedures must also be in place to properly mitigate this risk.

4.2.4 Applications of Hydrogen Energy

The ultimate goal of any new form of energy is to improve the global energy portfolio while minimizing social and environmental impacts. Hydrogen energy produced from artificial leaf technology holds significant potential due to its wide range of applications. According to the *Fueling Development* report by the U.S. Office of Technology Assessment, the two largest barriers to widespread use of hydrogen energy are storage and cost of production (U.S. Congress, 1992). However, compared to natural gas or coal, artificial leaf technology is capable of harnessing a renewable source of energy, sunlight, to produce hydrogen via the photovoltaic-driven electrolysis of water. And since the artificial leaves can be used to produce energy locally, island and coastal regions will no longer have to depend on fuel imports or foreign electricity grids. The main challenge, however, is producing the hydrogen fuel at lower cost. The cost of hydrogen—regardless of the production technology—must be less than the $4/gallon gasoline equivalent in order to be competitive in the transportation sector. To reduce overall hydrogen cost, research is focused on improving the efficiency and lifetime of hydrogen production technologies, as well as reducing the cost of capital equipment, operations, and maintenance.

After the hydrogen is produced by the artificial leaf technology, a pipe-like structure, resembling that of a desalination plant, will transport the hydrogen to the shoreline. There, one will find two major components: hydrogen storage tanks, to collect the compressed hydrogen, and fuel cells, to burn the hydrogen and generate usable energy (Figure 16).

Figure 16. ASME Spherical Pressure Vessels for hydrogen storage (left) (Tarsco, n.d.) and European MW-scale industrial hydrogen fuel cell power plant (right) (FuelCell Energy, n.d.).

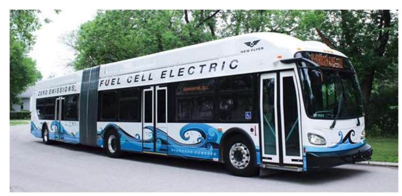
In a fuel cell, the hydrogen combines with atmospheric oxygen to produce electricity and clean water, along with a small amount of heat. Fuel cells are often compared to batteries because they both convert energy produced by a chemical reaction into usable electrical power. Therefore, depending on what function the hydrogen will serve once it is in a usable form, in either electricity generation or the transportation sector, artificial leaf developers must consider the end user of the hydrogen energy when constructing the onshore components of the project.

One of the primary uses of hydrogen today is electricity production. Large fuel cells can provide electricity for backup or emergency power in buildings, and supply electricity to places that are not connected to electric power grids. As of October 2019, there were about 80 fuel cell power plants operating in the U.S., reaching approximately 190 megawatts (MW) of total electric generation capacity ("Hydrogen Explained," 2020). The largest is a 27-MW project at the Red

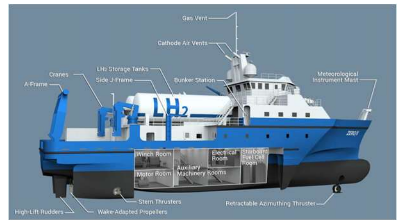
Lion Energy Center in New Castle, Delaware, which uses hydrogen extracted from landfill gas (a renewable biogas produced from landfills) to power the fuel cells.

In order for a community to experience the maximum benefits of artificial leaf development, they must consider how they can integrate systems powered by hydrogen fuel across their current energy infrastructure. The transportation industry is one of the most promising avenues for a global transition towards hydrogen energy (Table 2).

*Table 2***.** Potential hydrogen fuel cell-powered vehicles within the transportation sector.

Vehicle	**Description**	**Example**
Cars	Alternative fuel vehicles, like electric cars, are already popular amongst car lovers. Hydrogen fueling stations can be constructed to look exactly like traditional gas stations to reduce societal impact. *Pictured: Hydrogen Station in Riverside, CA*	
Buses	In regions with effective public transportation, fuel cell buses would have little to no impact on local residents. Bus drivers must be properly trained to use the new filling system. *Pictured: Fuel Cell Bus in Champaign, IL*	
Trucks	Large semi-trailer trucks are some of the highest polluters on the road. Fuel cell trucks can be more efficient with sleeker, more aerodynamic designs. *Pictured: Hyundai Fuel Cell Truck Concept*	
Boats	Yachts, cruise ships, ferries, and other tourist vessels can use a zero-emission drive train powered by hydrogen energy while attracting more customers with a green brand. *Pictured: Golden Gate Zero Emission Marine*	

<table>
<tr>
<td>Shipping Vessels</td>
<td>Maritime shipping is a major source of ocean pollution. However, developers must make sure fuel cells do not add too much weight to hydrogen-powered vessels to make them ineffective.

Pictured: Zero-V Fuel Cell Research Vessel</td>
<td>
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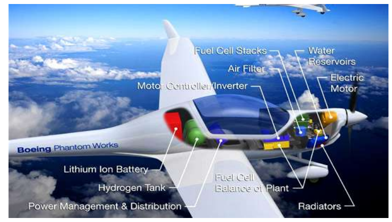
<tr>
<td>Airplanes</td>
<td>Airplanes are the most energy-intensive vehicle, so hydrogen-powered planes could drastically improve this statistic. Another application could be in the Air Force, which consumes more energy than any other branch.

Pictured: Boeing Fuel Cell Airplane</td>
<td>
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Production of hydrogen-powered cars is limited because people will not buy them when hydrogen refueling stations are not easily accessible; yet companies are not building new refueling stations because demand is low, as there are no new customers purchasing hydrogen-powered vehicles. According to the U.S. Energy Information Administration, the U.S. has a total of about 60 hydrogen refueling stations. And out of the 40 currently available for public use, nearly all of them are found in California ("Hydrogen Explained," 2020). The integration of a program to help fund the development of publicly-accessible hydrogen refueling stations throughout California has heavily promoted a consumer market for zero-emission fuel cell vehicles across the state, and has the potential to be expanded to a national level. This same "chicken or the egg" paradox can be seen across the entire transportation sector. Unlike industrial-scale fuel cells, any hydrogen-powered vehicle will require large storage tanks and fuel cells to be built into the vehicle frame due to its low energy density (Figure 17).

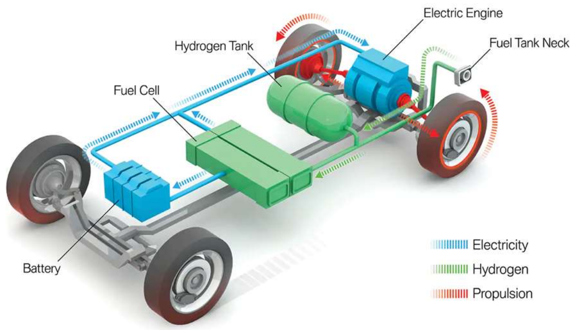

Figure 17. Storage, fuel cell, and battery found on hydrogen-powered vehicles (BMW, n.d.).

The demand for transport services will continue to grow around the world (especially in developing countries) driven by population growth, economic growth, structural change, and the transition to more urban industrial economies. However, not every coastal community is in a developing economy, which is why it is important to note that this emerging technology can also be integrated into already-existing energy and transportation infrastructure as well.

While transportation and electricity are the two major end users for hydrogen energy, there are endless innovative applications of hydrogen energy. Some of these include, but are not limited to, feedstock and fertilizer production, gas welding, hot air balloons, petroleum refinery, ultraviolet lamps, potentiometry and chemical analysis, mass destructive bombs, structural identification, gas chromatography, rocket fuel for space programs, and more. Due to its strong potential, hydrogen is an up-and-coming energy carrier that is a speculative, yet highly probable long-term solution to the global energy crisis.

4.3 Identifying the Driving Forces

As previously identified, the global community has depended on fossil fuels for decades, leading to extensive amounts of infrastructure, economic support, and political latching. Unfortunately, nonrenewable resources are unsustainable, and the world must commit more intentionally to renewable resources. Even if only on a small scale, the artificial leaf technology is a valuable tool for island communities to work towards self-electricity production with freshwater byproducts. The specificity of this technology as defined by this project—a water-splitting solar cell that would work best as floating on rafts in the sea—holds value in different ways based on the cultural and political implications in these communities. For example, a viable island community for this technology may resist it due to labor wages, lack of scientific support, or lack of qualified workers. In this case, it is up to researchers to determine whether communities may import more technical laborers, change renewable energy policies, or even change parts of their culture to either adapt or deter these emerging technologies.

Pertaining to this project, the approach that informed this component was inspired by a comparative analysis of three chosen island communities. This required cultural research and collecting information such as a community's willingness to adapt, fraction of population in support of the new technology, and effectiveness of the integration of the technology. These variables will be used in a system dynamics model based on the Bass Diffusion Model to determine how communities may react based on their cultural attitudes (Mahajan et al., 1990).

4.3.1 Conducting a Scenario Analysis

The concept of a scenario analysis is defined as, " a process of analyzing future events by considering alternative possible outcomes" (Spaniol & Rowland, 2019). For this report, a scenario analysis tool was utilized to explore the relationships between the proposed scenarios. When conducting a scenario analysis, one must pay close attention to the scenario crosses, or important drivers, selected for each axis in the quadrant to properly analyze a particular scenario. The potential scenario crosses were outlined in a quadrant to overlay four variables (Figure 18).

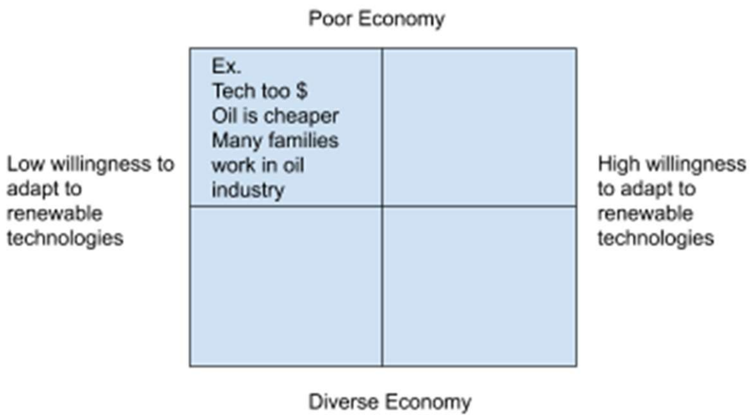

Figure 18. Scenario analysis quadrant used to categorize futuristic variables.

Inspired by the quadrant above, the scenario analysis exercise conducted for this project investigated two very important scenario crosses. The first two drivers are related to the impact artificial leaf development has on the surrounding community, which are represented by the range of potential change in the community along the horizontal axis. The second two drivers are related to how a large industrial company would differ from a smaller, more local grass-roots company in artificial leaf development, which are represented by the size of the business along the vertical axis (Figure 19).

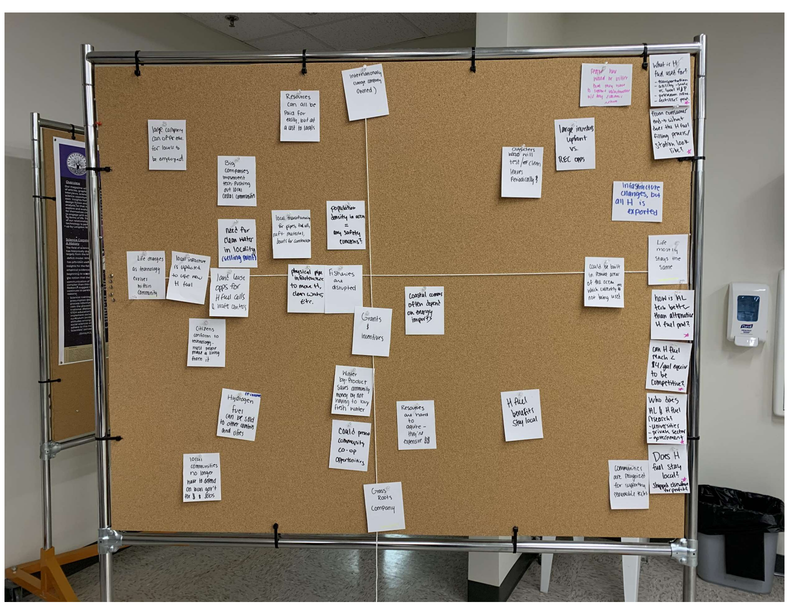

Figure 19. Scenario analysis exercise regarding artificial leaf development.

The theme of each quadrant is determined by each axis. So, for example, the bottom left quadrant represents a project that is constructed on a grass-roots level and has minimal impact on the surrounding community, while the top right quadrant represents a project that is constructed by a large industrial group and has a significant impact on the local community. The line of cards along the right-hand side of the board was a place for the student researchers to place miscellaneous facts and questions as they came up during the exercise.

This exercise was conducted using the materials available in the JMU STS Futures Lab, which is a platform that embraces interdisciplinary collaboration to better understand and address the complexities that arise at the interface of science, technology, and society. Their particular emphasis on the mid- to long-term futures of technological trajectories aligned very well with this investigation into the future development of artificial leaf technology. The experiment took approximately one hour, and encouraged the investigators to think critically about the problem at hand while looking outside of the box to create innovative solutions. As a result of this activity, the experimenters wrote a list of questions that arose while trying to analyze these two major concerns related to artificial leaf development. The critical questions were as follows:

1. What is hydrogen fuel used for (transportation, utility-scale versus local heat and power, petroleum refinement, fertilizer production, etc.)?
2. From the consumer end, what does the hydrogen filling process/station look like?
3. How are artificial leaves better than alternative methods of producing hydrogen?
4. Can hydrogen fuel reach a $4/gal equivalent or less in order to be competitive?
5. Who does the artificial leaf/hydrogen research (universities, private, federal, etc.)?
6. Does hydrogen fuel stay local? Or is it shipped elsewhere for profit?

4.3.2 Utilizing the STIR Protocol

Another method used to determine the integration of the artificial leaf on a community scale is the Socio-Technical Integration Research (STIR) method developed by Erik Fisher at Arizona State University (Fisher & Schuurbiers, 2009). During prototype testing, a chart was used to identify short-comings in either the research or manufacturing processes. Considerations, alternatives, and recommendations were brainstormed based on problems in the lab and opportunities for improvement. For example, the exercise below provokes researchers to think about the base material for the solar cell (Figure 20). This example was chosen because the researchers felt it best represented the technicality of the societal conversations. The goal was to demonstrate how a seemingly steadfast method in the materials science lab could be changed with this procedure. This validates the importance of the STIR protocol.

What opportunities and/or problems are you grappling with? • Is GaAsP the best material for our solar cell? • Manufacturing pros and cons? • What are our testing protocols? • How could we be skewing data? • What material could be more easily accessed in local communities?	**What are the alternatives you need to consider? What kinds of expertise, skills, and perspectives will be needed?** • Using Si wafers instead • Need materials science expertise to determine which could produce more electricity • Long term cost/ benefits • Which material is easier to manufacture and import?
Considerations: What are important factors and issues to consider? Who might care? • GaAsP dust is more toxic • Both materials corrode in water • Si is more efficient —> handles longer wavelength • GaAsP has lower efficiency loss at high temps • Produces more power/area • Si is ~1000x cheaper to make	**What are your recommendations or desired outcomes? What decision might you make?** • We want earth-abundant, non-toxic materials that are low-cost. • OUTCOME —> our choice of materials is based on: 1.Technical suitability for proof-of-concept research devices 2.Availability 3.Experience with processing of PV 4.Experience with processing of photo-electrode

Figure 20. STIR exercise for GaAsP in artificial leaves.

This particular research project was the first time that undergraduate researchers have used the STIR protocol, especially while simultaneously conducting experiments in the lab.

4.4.3.1 Materials

During the STIR exercises, a printout of the STIR protocol, developed by Erik Fisher and modified by Dr. Shannon Conley, was used. The four sections included:

1. What opportunities and/or problems are you grappling with?
2. Considerations: What are important factors and issues to consider? Who might care?
3. What are the alternatives you need to consider? What kinds of expertise, skills, and perspectives will be needed?
4. What are your recommendations or desired outcomes? What decision might you make?

4.4.3.2 Methods

The guiding questions above were brought into the lab referred to near the end of each three-hour lab session. Each exercise was conducted collaboratively between the two student researchers. Some were done with just the student researchers, while others, such as the one presented in Figure 20, were completed with Dr. David J. Lawrence in the Center for Materials Science at JMU. After completing the lab work for the day, the team would reflect on the materials and methods used to create the PV cell and additions by following the 4 sections of the protocol from top left, counter-clockwise. For example, the primary goal was to identify problems in the lab, like poor efficacy of the PV cell, or opportunities like how to use less material with the same efficacy. In this example, the researchers were grappling with whether the base of the solar cell, GaAsP was the most cost efficient and solar efficient material. It is important to point out that this example heavily simplifies the problem addressed, though this was discovered with further research. This is what was being tested in the lab at the time, and what yielded the best results, but the researchers wanted to know if another material would make the manufacturing of the product better for large scale artificial leaves. For the second quadrant, the researchers were urged to determine considerations. This quadrant helped the team refocus on the original question: Is GaAsP the most efficient solar cell material? This is where other materials were considered and compared. In this example, it was determined that silicon (Si) is another usable material. After conducting research during this time to compare and contrast these two materials, it was determined that GaAsP had been proven to be more effective in a lab setting for producing hydrogen. However, GaAsP typically is more dangerous for manufacturing because of the toxicity of dust particles. Compared to GaAsP, Si is less dangerous, is about 1000 times cheaper to use on a large scale, has lower efficiency loss at higher temperatures, and can handle a longer wavelength which would be needed in larger solar panels (Abate, 2015). This led to the question of whether GaAsP is better for artificial leaf prototypes than Si.

This thought process led to more in depth and difficult realizations. In reality, determining what material to use was far more complicated than just looking at PV efficiency. While Si is more efficient than GaAsP if just PV efficiency is considered, a tandem artificial leaf that integrates a PV cell with a photoelectrode ($BiVO_4$) involves many other factors. There are tradeoffs between PV characteristics and photoelectrode characteristics that make optimization more complicated. It is important to get the most PV voltage possible while still providing enough current to supply the photoelectrode at its optimum operating point. This will generally be different from the max power point for the PV alone. Also, PV and photoelectrode must each be able to utilize part of the solar energy incident on the leaf in an optimized fashion.

When completing the third quadrant, these questions were considered more in depth. This time, the researchers discussed what expertise was needed to make each material and alternatives that had yet to be considered. This quadrant was very important in challenging the way in which the researchers imagined the entire manufacturing process from cradle-to-grave. This led to increased research into the two materials, including the effects of being submerged in saltwater, time it would take to use each material, and adding extra layers of p-n junctions and co-catalysts. The researchers discovered that while Si wafers were more versatile for solar cell production for houses and businesses, the GaAsP provided a relatively high band gap, which enabled it to produce up to 1.2 V when used in a PV cell, compared to only about 0.6 V for Si. It was also more effective in conducting electricity when adding other materials on top. Therefore, it was decided that GaAsP would be used for testing purposes to improve the efficiency of the water-splitting research. A large-scale manufacturing process, however, would likely switch to either Si wafers or a combination of the two for the PV cell. This concluded the fourth quadrant, which explored recommendations and outcomes.

Before doing this STIR protocol, the choice was taken at face value as previous research teams used it as well. This was an example of a midstream modulation. Like many of the other STIR protocol sessions, utilizing these thought-provoking questions allowed the researchers to take a step back and research the product through the eyes of a social scientist. After identifying the weaknesses in the realities of energy consumption, conservation, and community engagement with new solar technologies, adaptations were made mid-project to create a more holistic and centric product goal. This created an opportunity to challenge a weakness that could hinder the success of scaling up, as well as providing a sustainable product at the lowest cost. These integrative questions provoke researchers to consider different futures so they can quickly adapt to the market as the manufacturing and marketing of small-scale artificial leaf technology begins.

4.3.3 Creation of a System Dynamics Model

Based on the aforementioned methods, below are the objectives followed to model an emerging solar technology, the artificial leaf (AL), in a coastal community.

1. Identify stocks that play a role in the adoption of the artificial leaf as an emerging technology by considering relevant stakeholders and corresponding flows between them.
2. Create a basic Vensim model with functional equations that demonstrates a graph with S-shaped growth of artificial leaf adopters as the technology emerges.
3. Add to this first model with a research and development (R&D) stock that shows how investing in research will increase the adopters over time.
4. Once the model is properly constructed, test each individual rate to see which variables contribute significantly to the behavior of adopters and non-adopters of the artificial leaf.
5. Find the optimal model structure that maximizes the "Actual Adopters of the AL" and minimizes the "Actual Non-Adopters of the AL" based on these individual rates.

The systems dynamics model of Artificial Leaf Emergence and Adoption was constructed using Vensim modeling software (Figure 21).

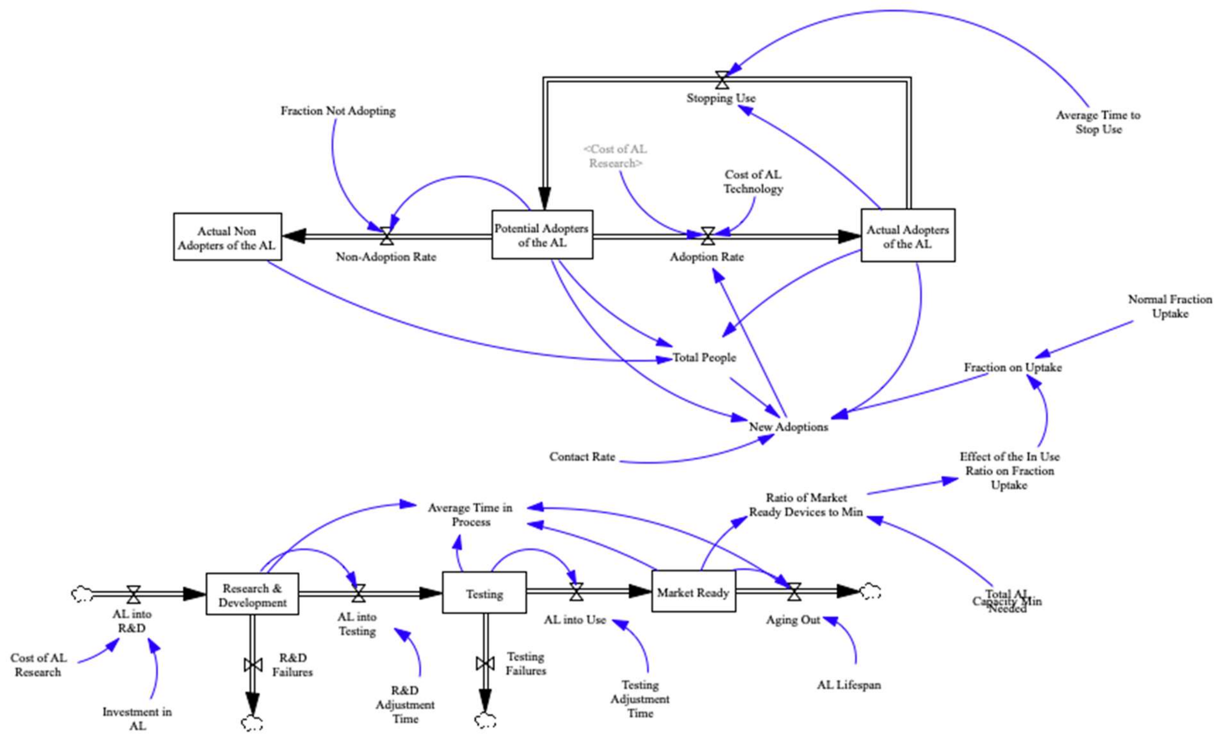

Figure 21. Systems dynamics model of Artificial Leaf Emergence and Adoption.

As with any emerging technology, there will always be adopters and non-adopters. The artificial leaf adoption model shows the growth in adopters as S-shaped growth, inspired by the Bass Diffusion Model (Boswijk & Franses, 2005). Additionally, there is an emphasis on the contribution of R&D into the successful deployment of the technology. As the cost of AL research balances with the number of dollars in investment, the R&D increases. Eventually, these three levels along the bottom row influence the number of adopters. In other words, the more R&D, the more faith citizens will have in investing in the technology, leading to more adopters. It is also unlikely that with more R&D, the technology will fade out after the market is saturated. Rather, the R&D would continue to make the technology even better with new iterations every few years, creating a desire for adopters to purchase again. The graph below demonstrates how the adoption of artificial leaf technology has S-shaped growth (Figure 22).

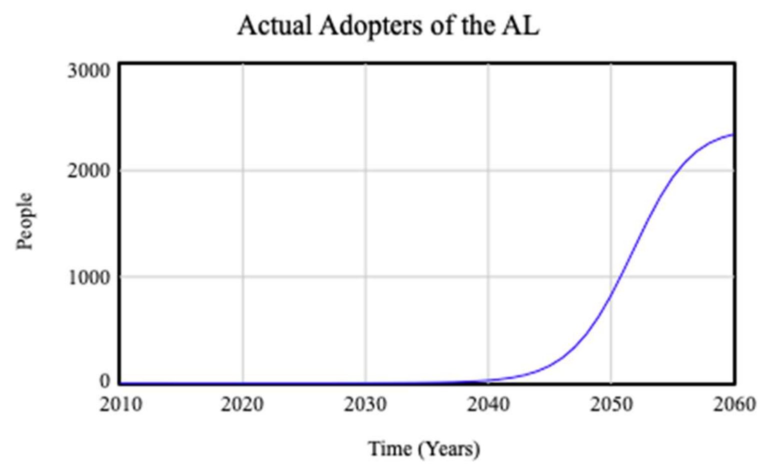

Figure 22. Graph of actual adopters of the artificial leaf.

For the people represented in the model that are not included in the graph above as "Actual Adopters of the AL" because they either never adopted or are no longer using the technology, they move into the stock called "Actual Non-Adopters of the AL." The graph of this behavior is presented below, with the non-adopters eventually reaching its peak, meaning there are no more non-adopters entering this stock after a given amount of time (Figure 23).

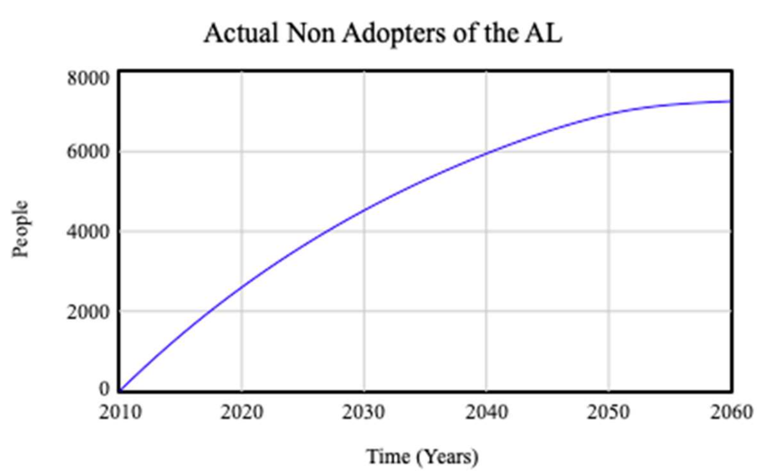

Figure 23. Graph of actual non-adopters of the artificial leaf.

The goal of this project is to increase actual adopters while decreasing actual non-adopters. Within the structure of the model, there are a total of twelve variables that are alterable to change the model output. Once the model was constructed, each rate was tested individually to see how they can be changed to increase adopters and decrease non-adopters. In order to achieve the previously stated goal, the table below shows the changes that can be made to each individual rate to generate the desired behavior (Table 3).

Table 3. Results of variables changed between two stocks in the system dynamics model.

Variable Changed	Effect on Actual Adopters	Effect on Actual Non-Adopters
+ Cost of AL Research	no effect	no effect
- Cost of AL Technology	increases (+)	decreases (-)
+ Average Time to Stop Use	increases (+)	decreases (-)
+ Contact Rate	increases (+)	decreases (-)
+ Investment of AL	increases (+)	decreases (-)
- R&D Failures	increases (+)	decreases (-)
- Testing Failures	increases (+)	decreases (-)
- R&D Adjustment Time	increases (+)	decreases (-)
- Testing Adjustment Time	increases (+)	decreases (-)
+ AL Lifespan	increases (+)	decreases (-)
- Total AL Capacity Min Needed	increases (+)	decreases (-)

Based on the results presented in Table 3 above, it is apparent that the only variable that did not have a significant effect on either stock was the "Cost of AL Research." This does not have a significant effect because after studying the model structure, the effect is shown through the "Cost of AL Technology" itself. Based on these results, the graphs presented below were created based on manipulation of the variables above (Figure 24).

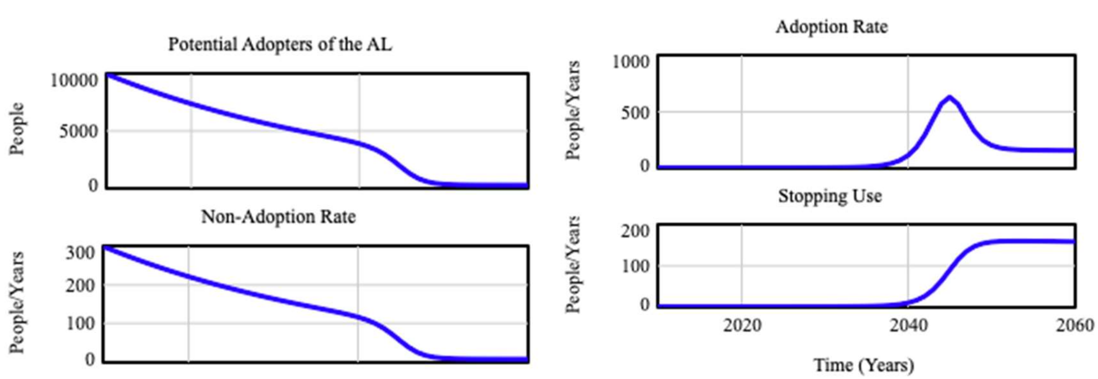

Figure 24. Behavior over time graphs (in years) related to the artificial leaf.

These graphs above demonstrate that as potential adopters decrease over time due to the increase in adoption rate, or more people adopting the technology, the adoption rate and the stopping of use come to a plateau because there are no more people who want the technology and do not already have it. Because the goal is to retain customers as the original artificial leaf purchases expire, the adopters must be able to move back into the potential adopter level. This flow is shown below (Figure 25).

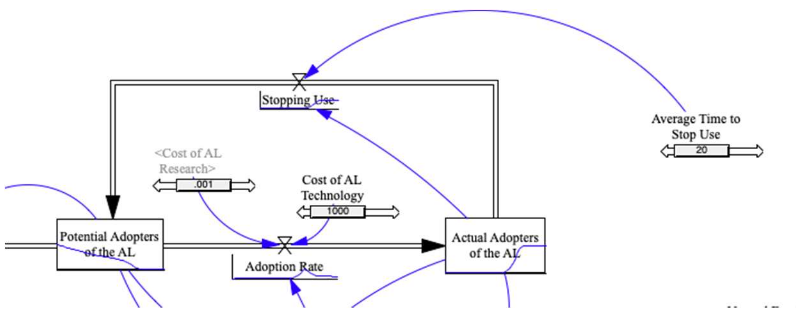

Figure 25. Flow of potential adopters to actual adopters to overcome market saturation.

As shown above, the rate flowing between potential and actual adopters is meant to decrease the number of non-adopters over time. By first appealing to the more environmentally-conscious customers, developers can hope that the other community members will follow suit.

Constructing the systems dynamics model was a crucial step in identifying the driving forces related to artificial leaf development. By combining this model with the scenario analysis procedure and STIR protocol, the researchers were able to effectively define the parameters that will allow artificial leaf technology to thrive in the future.

4.4 Defining the Critical Uncertainties of Artificial Leaves

Solar panel manufacturing has greatly improved globally since the beginning of renewable energy pushes in the late 20^{th} century, amidst challenges caused by solar tariffs. According to Paul Hawken in his book "Drawdown: The Most Comprehensive Plan Ever

Proposed to Reverse Global Warming," the net cost of solar energy today is about $80.6 billion, while the net gain in energy cost savings is projected to be $5.02 trillion by 2050 (Hawken, 2017). For the JMU artificial leaf in particular, it takes one hour to produce 1.8×10^{-5} moles of hydrogen gas. This means that 0.42 cm^3 of hydrogen gas is created after one hour of using the artificial leaf prototype, with an area of 1 cm^2, per results currently observed in the lab.

4.4.1 Total Saltwater Area Required Calculations

Because each island has a different average daily solar radiation and household energy usage, the area of artificial leaves needed to power a whole community will also differ. The standard household energy usage per day in Malta, for example, is 18.16 kWh/day, and the global horizontal irradiance (GHI) is 5.29 kWh/m^2/day. With regards to solar PV installations, the GHI refers to the "total solar radiation per unit area that is intercepted by a flat, horizontal surface" (Lucky et al., 2014). If the artificial leaves are assumed to be cost-effective for manufacturing at 10% efficiency, then the average solar energy consumed in the water-splitting reaction is 181.6 kWh/day to power a single home in Malta. Based on the assumption that an average-sized coastal community in any of these regions has about 1,000 homes, the saltwater area required for the artificial leaves to power 1,000 homes in Malta based on the global horizontal irradiance (GHI) of the region can be determined using the calculation below:

$$\frac{181{,}600\ kWh/day}{5.29\ kWh/m^2/day} = 34{,}000\ \mathrm{m}^2$$

Using the equation above, all of the relevant data needed to calculate the saltwater area required to power 1,000 homes on each of the three islands is recorded below (Table 4).

Table 4. Calculating the required saltwater area for artificial leaves.

Location	Global Horizontal Irradiance, GHI	Average Household Energy Use per Day	Saltwater Area to Power 1000 Homes	Data Sources
	$kWh/m^2/day$	kWh/day	m^2	
Haiti	5.65	0.26	460	Lucky et al. (2014) Stuebi & Hatch (2018)
Hawaii	5.72	16.60	29,000	"Solar Power in Hawaii" (2020) Crees (n.d.)
Malta	5.29	18.16	34,000	Sciubba et al. (2012) Nikiel & Oxley (2011)

Given the area of an average American football field is 5,350 m^2, it would take the equivalent of nearly 6.5 football fields of ocean surface area for the artificial leaves to consume enough solar radiation per day to power a Maltese community of 1,000 homes. However, the energy consumption in Haiti is far lower than Hawaii and Malta, as it is one of the lowest in the world. From an economic perspective, the feasibility of artificial leaf development in Haiti would need to be evaluated based on the realistic energy needs of their coastal communities compared to the costs of the project. Regardless of where the artificial leaves are deployed, it will require a substantial efficiency improvement from the leaves (500% increase or more for the JMU devices) for this technology to be widely adopted. However, it will always be in a nation's best interest to create a diverse energy portfolio so they are not depending on one source entirely to ensure resiliency when difficulties arise. It should be noted that water splitting devices with efficiencies up to 19% have been reported, however, those devices employed expensive materials and expensive fabrication processes that are not suited for scale up to manufacture large areas of artificial leaves (Cheng et al., 2018).

4.4.2 Volume of Pure Water Produced Calculations

In addition to determining the saltwater area required to power a coastal community, it is also important to consider the volume of pure water that can potentially be produced from these artificial leaf systems. Assuming very efficient fuel cells (near 100%), the electricity used in a single household per day is equal to the energy in the hydrogen that must be burned. Given the lower heating value of hydrogen gas (33.3 kWh/kg) the volume of pure water produced from this reaction to supply coastal communities of 1,000 homes is calculated below (Table 5).

Table 5. Calculating the volume of pure water produced from artificial leaf technology.

Location	Energy to be Burned in Hydrogen per Home	Amount of Hydrogen Burned per Home	Moles of Hydrogen Burned per Home	Moles of H2O produced per Home	Amount of Water Produced per Home	Water Produced for 1000 Homes
	kWh/day	kg/day	mol H/day	mol H_2O/day	L/day	L/day
Haiti	0.26	0.01	7.81	3.90	0.07	70
Hawaii	16.60	0.50	498.50	249.25	4.49	4.500
Malta	18.16	0.55	545.35	272.67	4.91	4,900

Once again, since Haiti has such a small rate of energy consumption compared to the other two islands, constructing a smaller project to fulfill energy needs in Haiti will lead to a far less pure water being produced. While some water production is better than none at all, the locals of these coastal communities in Haiti are in desperate need of this pure water source, so the size of the project will need to be evaluated based on both their energy and water needs. Hawaii and Malta, on the other hand, both show strong potential for the production of pure water for their citizens, with Malta at the front of the pack with 4,900 liters of pure water produced per day from an area of 34,000 m^2 in the ocean taken up by these artificial leaves.

4.4.3 Manufacturing and Life Cycle Predictions

Due to the potential environmental harm of heavy metals when not disposed of properly, the GaAsP and other artificial leaf components must be either reused or broken down. This lowers the cost of manufacturing, and the long-term use of the artificial leaf will help to offset the mining and emissions of nonrenewable resources to create them. The hypothetical manufacturing process of artificial leaf prototypes is illustrated below (Figure 26). This is a very simple illustration that would need a lot of further development and research before being implemented into a large-scale manufacturing process. For example, the development of the thin-film PV technology needs to be perfected to generate ~1 Volt. Second, the development of spray pyrolysis or other deposition processes need to be streamlined. Third, the $BiVO_4$ needs to be substantially improved to achieve better efficiency.

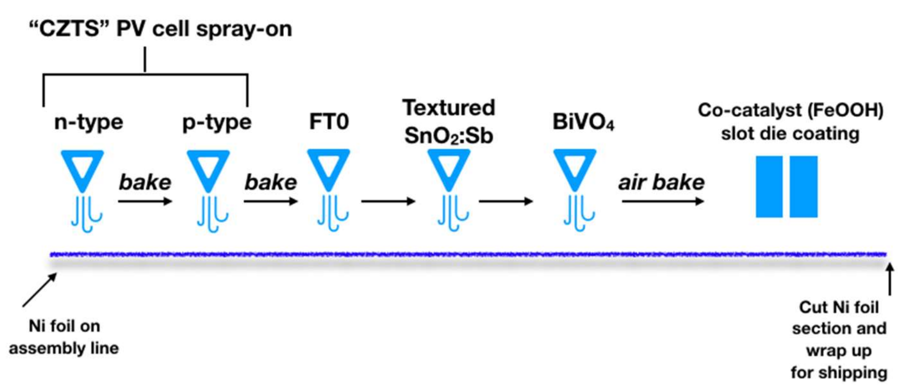

Figure 26. Hypothesized design of a large-scale manufacturing system (Lawrence, 2020).

While researchers have not yet been able to predict a precise anticipated lifetime for the leaves, it will likely be comparable to the lifespans of similar technologies. For example, solar panels have an average lifespan of approximately 25 years, while floating PV systems have proven to be up to 16% more efficient due to the water's cooling effect, which helps to reduce thermal losses while extending their life (World Bank Group et al., 2018). However, these technologies do not experience the same level of corrosion from the saltwater as a raft of artificial leaves would because the leaves will be entirely submerged. This is why researchers are working tirelessly to find the perfect balance of chemical layers to protect the PV cells without limiting their efficiency. For example, wave energy converters made with corrosion-resistant metallic alloys are subject to similar conditions, yet still experience 20-50 year average lifetimes depending on the model and materials used. Given the lifetimes of these parallel technologies, it would be reasonable to estimate that with optimum efficiencies and adequate protection from saltwater corrosion, artificial leaves could also experience lifespans of at least 20 years.

4.5 Generating and Validating Scenarios with a Comparative Analysis

The considerations above informed an in-depth comparative analysis of the following three potential sites for artificial leaf deployment: Haiti, Hawaii, and Malta. These three islands were chosen based on their geographic characteristics and desire for both renewable energy and clean water sources in an effort to determine the best site to deploy this emerging technology. Based on the location and energy needs of the surrounding community, multiple rafts of artificial leaves can be anchored side-by-side to build larger arrays. Highly comparable to floating fishing farms and floating solar arrays, large networks of artificial leaf rafts would be constructed in areas of the ocean free from large waves and extreme weather. In the case of a hurricane, tsunami, tornado, or other natural disaster, the best mitigation technique may be to construct the rafts in such a way that they are able to be removed from the water, off the shoreline, and stored until the extreme weather has passed. Then, the hydrogen produced by the artificial leaves will be transported back to shore, where it will be stored and burned in a fuel cell to generate electricity with a byproduct of clean water. A complete system may take many shapes, all depending on shoreline constraints and the available water surface area. Each raft will be designed taking local water depth, wave, current and wind conditions into consideration. The rafts will also be hydro-elastic, allowing the artificial leaves to move gracefully with the harmonics of the waves, as opposed to working against them. Basin tests and simulations must be conducted during the data collection stage in order to predict the system's wave capabilities.

Since no artificial leaves are currently in use, most of the research conducted for this report was inspired by already-existing wind and solar projects. There are many parallels between artificial leaves and floating solar PV systems currently in use. However, the development concerns associated with artificial leaves are very similar to that of offshore wind farms, which is why this report references the Siting Handbook from the American Wind Energy Association to inform artificial leaf predictions. Depending on the location, it is presumed that artificial leaf development and deployment will follow roughly these steps (AWEA, 2008):

1. Find available and usable space for the project area (both onshore and offshore).
2. Understand the available solar resource.
3. Determine distance from shoreline.
4. Conduct an initial site visit.
5. Establish access to capital.
6. Secure access to the project area.
7. Identify reliable purchaser(s) of the project.
8. Determine the end-users of the hydrogen energy.
9. Address project feasibility concerns (environment, politics, local community, etc.).
10. Obtain zoning and permitting expertise for the project area.
11. Establish dialogue between artificial leaf manufacturers and project developers.
12. Secure an agreement to meet operations and maintenance needs.

13. Procure equipment required for project construction.
14. Construct the artificial leaves, hydrogen storage tanks, fuel cells, etc.
15. Collect pure water from the fuel cells to be used by the local community with appropriate storage and distribution infrastructure.

4.5.1 The Artificial Leaf in Haiti

The nation of Haiti shares an island with the Dominican Republic (DR), on a landmass known as Hispaniola. Although these two countries share an island, there are still significant differences between them. In addition to the strong cultural differences between Haiti and the DR, the living standards in the DR are considerably higher than those in Haiti. This has led to shocking statistics, such as the fact that 98.5% of the population in DR has access to electricity, while only 37.9% (less than half) of the population in Haiti has access to electricity, according to global rankings developed by the World Bank ("Access to Electricity," 2014). This stark contrast between living standards in two bordering nations sharing nearly identical geography and coastlines is an interesting case study to investigate energy poverty in developing countries, and it provides a unique opportunity for the potential implementation of artificial leaf technology. While the hope would be to one day use this technology across all of Hispaniola, this particular analysis focuses solely on Haiti. Their most urgent need is to provide electricity to over 60% of their population, especially given their considerably low global ranking for energy poverty compared to their neighbor.

It seems the major causes for such low percentages of their population with access to electricity has been a combination of a heavy dependency on coal and trends of people attempting to illegally connect to the grid (Helmer, 2018). According to the ClimateScope 2018 report by Bloomberg New Energy Finance, 80% of Haiti's current energy supply comes from fossil fuel plants, with the remaining 20% from one large hydro plant and several smaller ones (BNEF, 2018). However, it appears that Haiti is not currently utilizing their prime solar resource given their geographic location and high radiation. On the contrary, solar company Aten Global recently announced their plans to construct a new 45-MW floating solar PV plant with battery energy storage in Jamaica, an island nation very close to Haiti ("Aten Global," 2020). Partnering with Derillion Energy of the UK and Renewable Energy Investments Ltd (REIL) of Kingston, Jamaica, they are excited about this newfound potential of harnessing solar energy in the Caribbean, which could serve as a case study for future projects in Haiti and beyond. However, the project will be built in the Mona Reservoir, which does prove to be a major difference when compared to artificial leaf development in the ocean.

The growth of solar energy solutions in Haiti, specifically the artificial leaf, could be a massive opportunity for economic growth in a region that seems to be in desperate need of a cultural shift towards clean energy. Not only will it bring more jobs to the area, which could help raise their overall GDP, but it will also make them more independent so they do not have to rely on coal and other nonrenewable energy sources, all while having a positive impact on the environment. However, there are some concerns that arise in this region of the world compared to the other areas considered in this case study, such as the increased risk of earthquakes, which could potentially destroy infrastructure needed along the coastline to harvest the hydrogen energy collected by the artificial leaves deployed in rafts offshore.

Haiti has been identified as a crisis area for not only energy poverty, but also providing easily accessible drinking water. According to the World Bank, less than half of Haitians in rural areas have access to potable water, leaving nearly 2 million Haitians drinking unsafe and contaminated water ("5 Things You Need to Know About Water in Haiti," 2015). Through nonprofits and other initiatives such as The Water Project, residents of underserved communities are slowly acquiring access to clean water. However, this is an expensive process that requires a great deal of funding, which is why the proposed artificial leaf technology presents a unique opportunity for Haiti to produce both renewable energy and clean water for locals.

As both the electricity and potable water sectors of Haiti are some of the most challenged in the region, it appears to be a promising location for the deployment of artificial leaves and other innovative energy technologies. The World Bank recently launched a project called "Haiti: Renewable Energy for All," whose job is to introduce more renewable energy to the area via improved grid development and increased solar PV investments (World Bank, 2017). There would be ample opportunities for artificial leaf expansions under this group, which is already working across Haiti to bring access to clean energy to the locals. Contrary to the other two islands being considered, bringing this technology to Haiti would bring a new electricity source to those who have never had it, whereas bringing this technology to Hawaii or Malta might just simply reroute where their residents are already receiving their energy from. This, however, can come with massive infrastructure concerns when constructing these large systems in a developing country that might not already have the economic and distribution framework necessary to support this type of drastic innovation. This is why future artificial leaf developers must first compare Haiti's current energy status to the DR to better understand why Haiti is not utilizing their natural resources to harvest renewable energy if they hope to bring this emerging technology to an area that appears to be in desperate need of change.

4.5.2 The Artificial Leaf in Hawaii

Given the current renewable energy climate in the U.S., Hawaii is a very intriguing option for deploying low-impact technologies near coastal areas. According to the International

Energy Agency, there are dozens of policies currently “in force,” including the U.S. Climate Action Plan, the Smart from the Start Initiative, and the Bureau of Land Management and Renewable Resources. Each has a policy target for multiple renewable energy sources, including bioenergy, geothermal, and solar, which fall under the policy categories of “Planning” and “Information Provision.” These are the policies that outline the current standards in the U.S. for emerging technologies like the artificial leaf. Then, to address any environmental concerns if a site were to be selected in Hawaii, an Environmental Impact Statement (EIS) is required under U.S. law to be completed and filed for approval prior to the construction of any project that may “significantly affect the quality of the human environment” (Hughes, 1975). However, in early 2018, a 30% tariff was issued on foreign-manufactured solar components, which scared many solar producers despite trying to encourage more U.S. manufacturing jobs (International Energy Agency, 2018). Even though this tariff has drastically impacted solar panel imports from countries like China, who are producing panels for very low cost, it does promote local manufacturing and energy production using the artificial leaf and other innovative technologies.

However, there have been other policies that curb this one. For example, Hawaii implemented a policy in April of 2018 that will change the revenue model for Investor Owned Utilities (Brown, 2018). This means that the incentives are much higher for citizens to build and invest in solar panels. Customers who produce more energy than they need will be paid back by the power companies. So, the more that utility revenues are linked to performance metrics, the more incentives there are for people to invest in solar energy, all while driving them away from nonrenewables. This policy stands out for the artificial leaf because this type of reward for consumers will make oil and gas far less desirable (Figure 27).

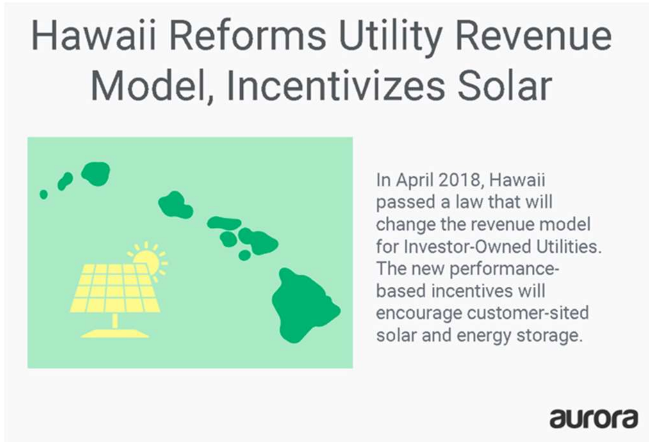

Figure 27. News headline about Hawaii incentivizing solar (Brown, 2018).

Hawaii is one of several island nations aiming to be 100% renewable by 2045. Currently, Hawaii gets 33% of its energy from rooftop solar panels and 60 utility-scale renewable energy projects, with a goal of reducing imported oil (Fialka, 2018). Not only does this save them money on expensive imports, but localizing a state's own energy source can significantly improve their economy, create local jobs, and improve resilience against natural disasters. Islands with their own energy supplies do not have to wait for a central hub to provide energy, so they can bounce back into normal transportation and electricity production faster, enabling families, communities, and medical services to react more effectively. While there is no precedent in Hawaii at the moment, there is a 4.4-MW floating solar system on a retention pond in Sayreville, New Jersey. It is currently the only array of this kind in the state, and the largest in the country, powering 100% of the local water treatment plant (Ludt, 2020).

Although Hawaii's energy infrastructure seems to be a perfect fit for introducing artificial leaf technology, it does not have the same urgent need for clean water as the other two island communities examined in this report. According to the Water Quality Plan prepared by the Environmental Health Administration's Safe Drinking Water Branch of Hawaii:

> From 1997-2014, the Hawaii Drinking Water State Revolving Fund has financed over \$149,000,000 in county water supply projects, including treatment plants, new drinking

> water sources, and the replacement of aging water lines and storage tanks. The resulting public health benefits and water and energy savings for over 1 million rate-paying residents statewide, coupled with the favorable debt service opportunity for the county entity (interest rates vary between 1% and 2% depending on the project loan amount), is a win-win for all parties. In addition, the Fund continues to provide additional subsidization (zero percent interest + principal forgiveness) to a select few qualifying "green" projects that provide water or energy efficiency benefits, thus reducing the effective interest rate to even lower levels. Significantly, most of the Program's financed projects have benefitted small water systems serving less than 10,000 persons ("Water Quality Plan," 2014).

Even if Hawaii is not in urgent need of clean water systems, it is clear that they are committed to providing clean water to their residents. And because the artificial leaf can produce both renewable energy and clean water locally, it would be an excellent green solution under the Hawaii Drinking Water State Revolving Fund.

Once this infrastructure is in place, it can serve as a model for the entire the Indo-Pacific region. For example, scientific tools and techniques that address problems such as erosion, ecosystem changes, and seawater quality monitoring to regulate marine pollutant levels in the ocean can be implemented within the artificial leaf infrastructure off the coast of an island community that chooses to adopt this technology. Since they would have already set aside the space where the artificial leaves would be deployed for non-recreational use, this area would ready for scientific research as well, so these supplemental technologies can be included without requiring significant infrastructural additions that would otherwise occupy a greater coastal area, which is often precious to locals.

4.5.3 The Artificial Leaf in Malta

Malta has been identified as at risk of energy poverty, as it is one of several island states in the EU that has heavily relied on imported energy in the past (Bouzarovski & Herrero, 2017).

The urgent need for electricity generation and water purification processes that are both inexpensive and environmentally-friendly make Malta an ideal site for artificial leaf technology.

Being the seventh most densely-populated country in the world, it is clear that Malta has faced challenges when it comes to both water and electricity resources (World Population Review, 2018). According to the Energy Poverty Conservatory, Southern Europe has the highest rates of air conditioning units in the EU, with 55.7% of Maltese homes containing units (Bouzarovski & Thomson, 2018). With average temperatures reaching nearly 90 degrees Fahrenheit in the summer, high energy consumption can become a financial burden for many. The need for air conditioning to make living situations more comfortable will also continue to rise with the increasingly noticeable effects of climate change.

As a member of the EU, Malta has an obligation to achieve specified energy standards. The EU published their Energy 2020 Strategy in 2010 with the following goals: reduce greenhouse gas emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, achieve energy savings of 20% or more, and require each member nation to achieve a 10% share of renewable energy in their transport sector (European Commission, 2010). EU member nations have an advantage over many other regions of the world when it comes to renewable energy development. With an abundance of available resources, such as wind, solar, and hydropower, these goals are extremely reasonable. Therefore, EU island nations should take advantage of their prime location and the supportive policies in place.

Fortunately, Malta has already taken major steps towards improving their internal energy poverty trends to achieve these standards by transitioning away from inefficient heavy oil- and coal-fueled domestic production. In an announcement made to the Maltese Parliament in 2018, Minister for Energy and Water Management Joe Mizzi stated that the combination of dismantling dirty power plants and investing in solar farms will help Malta reach these energy goals (Carabott, 2018). Along with the rest of the EU, Malta can help combat climate change and air pollution, decrease its dependence on foreign fossil fuels, and keep energy affordable for consumers and businesses through the attainment of these targets.

Only five percent of Malta's energy consumption comes from renewables, with the rest of the power fueling their electrical grid coming from natural gas, oil for backup, and an electricity interconnector with Sicily (U.S. Department of Commerce, 2019). Therefore, there is a niche in the energy market for artificial leaves in these island economies who are replacing their "legacy technologies" by shifting towards alternative energy sources.

Floating solar has already begun navigating its way into this niche market, as there is already an abundance of research pointing to the development of floating solar PV systems in Malta—more than most island nations. The University of Malta's SolAqua floating solar project addresses the issue of land scarcity in small island nations or large coastal cities where it is difficult to find adequate areas to build large land-based solar farms ("REWS," 2018). This EUR 200,000 project is a venture led by Prof. Luciano Mule'Stagno of the Institute for Sustainable Energy at the University of Malta. Serving as a case study for future floating solar arrays, this three-phase project began in late 2014. A prototype consisting of rafts with flexible panels was placed in Qalet Marku Bay, which has battled against the strong winds and waves of the open sea. After testing proprietary designs proposed by the University of Malta, researchers are now preparing for SolAqua 2.1, with a goal of eventually launching an enormous farm in Maltese territorial waters. If such a project meets the cost and power output targets, it would be possible to implement similar systems worldwide. This project has put Malta as a global frontrunner of research in floating solar panels. While there are several floating PV systems around the world, Malta has some of the first in open sea, while specifically studying factors such as the effect of salt drying on the panels on their output, cooling and reflection effects, and corrosion. This precedent of floating solar research stands as one of the strongest arguments in favor of artificial leaf development in Malta, especially because locals have already been exposed to the idea of electricity generation in the ocean, so it would be much easier to mitigate community concerns amongst fishing villages. Now, energy developers in Malta can use the same amount of space used for floating solar to produce both electricity and clean water with artificial leaf technology.

In addition to the solar infrastructure already in place and under development across the island, Malta has also begun researching and investing heavily in energy storage technologies. Hydrogen's ability to act as an energy carrier would be a competitive addition to storage technologies already on the market. And now that the EU is transitioning towards technologies that can help fulfill residential, commercial, and industrial needs, artificial leaves are exactly what Malta will need to cultivate their energy transition.

When considering both the main island and Gozo, Malta has over 250 kilometers (155 miles) of coastline. With easy sea access and a general social acceptance of renewable energy technologies, Malta has a promising opportunity to become a world leader in the implementation of artificial leaf technologies as their energy consumption continues to rise (Figure 28).

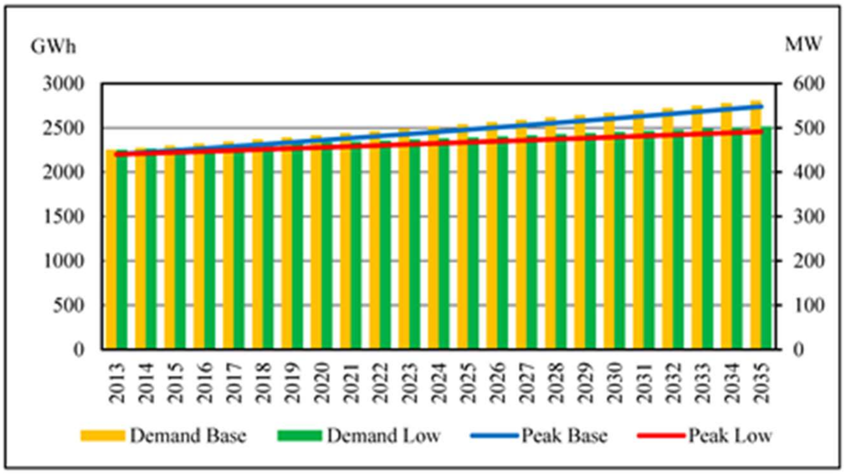

Figure 28. Annual energy and peak demand projections in Malta (Franzitta et al., 2016).

As an emerging technology, artificial leaves have the potential to help Malta work towards total energy independence. Not only can they produce energy in the form of hydrogen fuel cells, but the secondary byproduct of fresh water can also help provide potable drinking water for island citizens. According to an interview conducted by the European Environment Agency with Manuel Sapiano, Chief Policy Officer of the Energy and Water Agency in Malta, "Malta is one of the top ten water-scarce countries in the world," mainly because only half of Malta's water needs are produced naturally, with the rest coming from either desalination facilities or expensive shipments (European Environment Agency, 2018). And although desalination processes have undergone massive improvements in recent years, it is still an expensive process that is both time- and energy-intensive. Therefore, artificial leaf technology can provide Malta with autonomy over their energy and clean water sources rather than spending their limited energy supply on water purification systems.

4.6 Assessing Scenario Implications and Defining Possible Responses

After conducting a comparative analysis of these three potential sites, they were used to inform a futuristic investigation of creating design fiction scenarios for artificial leaf development. Design fiction is a tool used to inspire thoughtful reflection on how future technologies will impact society and human relationships while bridging the gap between science fact and fiction (Winner, 2004). Langdon Winner challenges the relationship between technology and society through "technologies as forms of life," which is the idea that as emerging technologies are developed and new worlds are built, new patterns of human activity will form (Winner, 2004). This is not a "secondary consequence" of emerging technologies—rather, it is an accomplishment to facilitate change in people's lives by adjusting their behavior to accommodate new technologies while creating systems that serve direct needs in the population. In this research, design fiction was used as an instrument to predict public acceptance based on two possible scenarios: centralized and decentralized development of artificial leaf technology.

Furthermore, in his work entitled "Do Artifacts Have Politics?," Winner describes a world where certain technologies are inherently political. On one hand, there are the centralized, more authoritative technologies, like nuclear power plants, which he claims are synonymous with accepting a "techno-scientific industrial-military elite" (Winner, 2004). On the other hand, there are decentralized, more democratic technologies, like solar energy, which can be constructed in a distributed manner to support local economies. When considering this spectrum, the production of hydrogen energy with solar technology in artificial leaves finds itself in a unique position, where it can include either or both of these power structures.

For a centralized system of artificial leaves, one might see massive fuel cells along shorelines burning hydrogen on an industrial scale. This power could then contribute to an electric grid spanning for thousands of miles while the pure water is stored and exported for profit, for example. Burning hydrogen in fuel cells can seem highly comparable to nuclear power, and could potentially help communities in need of utility-scale power (Figure 29).

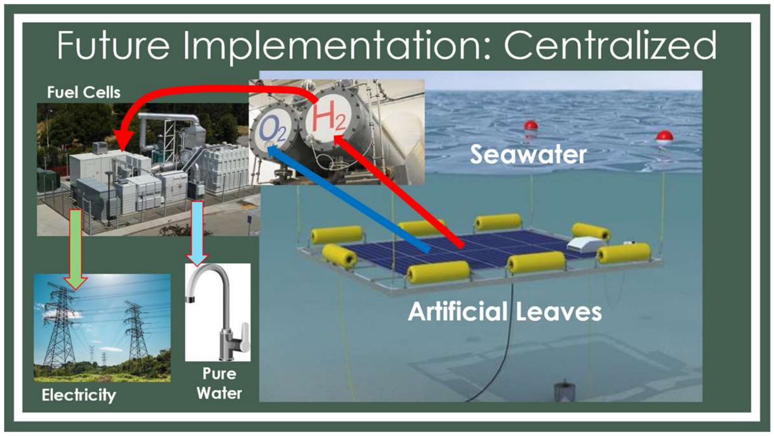

Figure 29. Centralized design fiction scenario.

On the contrary, a decentralized artificial leaf system would exist on a local, grass-roots level, where both the hydrogen energy and clean water are consumed locally. Through a political lens, artificial leaf technology could inspire coastal communities to become more independent from energy and water imports by managing their own production systems. By doing so, they could increase accessibility of both the hydrogen energy and clean water among locals (Figure 30).

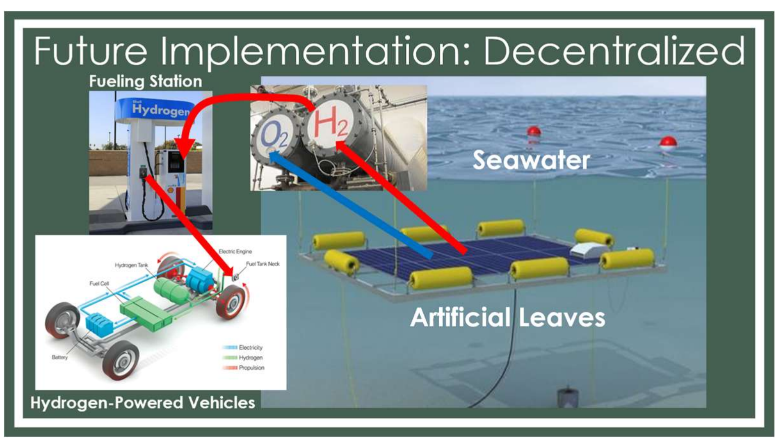

Figure 30. Decentralized design fiction scenario.

Artificial leaf developers must strongly consider both of these scenarios prior to construction. This will open the door to STS-inspired conversations surrounding the emergence of this new technology, and will have the potential to create new infrastructure for coastal communities in need, while also promoting sustainability and energy independence (Figure 31).

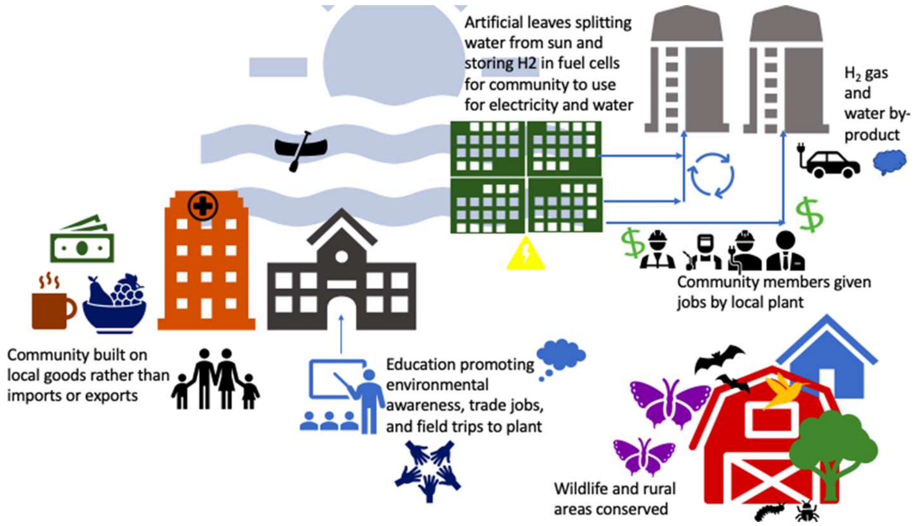

Figure 31. STS design fiction "ideal scenario" overview.

The schematic above serves as the ideal scenario of the STS component of this research, combining the comparative analyses and design fiction scenarios considered for artificial leaves. There is a community that does not depend on exports, creates jobs within their community with the manufacturing and caretaking of the artificial leaf and fuel cells. The community is integrated with both rural and urban areas and the wildlife is conversed. The community also focuses on educating children and members to be environmentally aware and invest in the energy system.

CHAPTER 5. CONCLUSIONS AND FURTHER RESEARCH

When it comes to artificial leaf research, it is not simply a matter of proving the concept of artificial photosynthesis, as this has already been done. The challenge now is to drive down cost, use sustainably-sourced materials, and increase the efficiency of artificial leaf prototypes.

The final method of Wade's procedure is "monitoring and updating scenarios." As this particular research was conducted only over a two-year period, this eighth step was not included. However, further study into possible artificial leaf scenarios is strongly recommended, and a more intensive investigation into the potential design fictions surrounding artificial leaf technology should be conducted prior to development.

5.1 Technical Component

Out of all the artificial leaves produced in the lab, the highest performing leaf achieved a maximum efficiency of 2.05%, which was an 11% improvement in efficiency than previous JMU prototypes. This calculation was done using the following equation:

$$Solar\ Energy\ Conservation\ Efficiency, \eta = \frac{chemical\ potential\ x\ current\ density}{insolation} \text{x } 100\%$$

$$\eta = \frac{1.23\,V\ x\ 1.67 \frac{mA}{cm^2}}{100\,\frac{mW}{cm^2}} \text{x } 100\%$$

$$\eta = 2.05\ \%$$

While this efficiency is only a fraction of the current efficiencies documented at well-known research institutions (~10%), these results show that each artificial leaf sample created and tested can effectively split water into hydrogen and oxygen gas using sunlight as its only input. The data shows promising results for artificial leaf development in coastal areas, and further research will strive to improve the co-catalyst to attain a higher solar energy conservation efficiency.

5.2 Social Context Component

There are ample political, economic, cultural, and environmental dimensions when considering artificial leaf development. Amidst many current debates surrounding peak oil and the impending challenges of global warming, it is clear that broader policies regulating energy development will need to have a top-down approach in order to fight climate change, while specific artificial leaf legislation should be enacted in smaller increments. But for now, the most attractive communities for deployment will be those that have the appropriate site characteristics, especially in developed countries, where policies pushing for renewable solutions already exist.

Because solar energy research is gaining momentum globally, scientists are racing to develop proper infrastructure for future renewable resources. The artificial leaf is just one example of how solar energy can be harnessed in a new way, and research institutions who have invested heavily in this technology have made major strides in the last five years. In fact, the artificial leaf was named one of the breakthrough technologies of 2017 by the World Economic Forum and Scientific American magazine due to its ability to convert solar energy to usable and storable fuel while only requiring limited infrastructure (World Economic Forum, 2017). However, before this technology can be deployed, researchers must first develop an efficient prototype that is economically viable in order to combat energy poverty in coastal communities.

Although they are not yet on the market, institutions across the world are developing prototypes with improved efficiencies and foresee significant advances over the next ten years.

It is clear that artificial leaf development is ideal in places where there is limited land availability and a need for both locally-sourced energy and clean water. While Haiti and Hawaii both have significant energy needs, Malta has shown an overwhelming amount of already-existing infrastructure and evidence that supports the deployment of artificial leaf technology. Therefore, after conducting a comparative analysis of the three potential sites and undergoing the design fiction exercise, Malta has been chosen as the most attractive location for future energy developers to construct the first site to deploy artificial leaf technology.

5.3 Combining STS Protocols with Lab Research

The decision to combine a materials science lab-based capstone with an STS-based overview was driven by the team's commitment to combine holistic problem solving with scientific discoveries and technological innovations. The researchers hope to motivate other students and faculty to move from a STEM platform to a STEAM platform, with a particular emphasis on the societal challenges that surround emerging technologies.

5.3.1 Jamie Mears Reflection

The Integrated Science and Technology program at JMU takes great pride in being the bridge between many technical fields and real-world applications in society. And after selecting the artificial leaf as the topic for this ISAT capstone project, the researchers quickly set up a meeting with Dr. Conley to see how an STS piece could be integrated into the report. Frankly, it was overwhelming at first to see the endless possibilities to turn a research-heavy project into a wholesome, well-rounded experience that included strategies to tackle real-world problems.

From the scenario analysis quadrant used to investigate a selection of scenario crosses, which significantly helped in the search for the most important drivers, to strategies for conducting interviews, like the STIR protocol, these processes significantly improved the researchers' ability to practice responsible innovation.

Conducting these procedures throughout the research proved to be far more valuable than any of the team members ever imagined. The STIR protocol, for example, challenged the researchers to consider the implications of each decision made in the lab. While it may have seemed odd at first, slowly they discovered that the more they asked these difficult questions to provoke thought and conversation, the more they found themselves in the lab having these conversations organically. Even though the structure of the STIR protocol is extremely valuable as a tool in the lab, it can be useful everywhere to encourage researchers to consider ethical dimensions and societal impacts.

At the end of the day, the hope is that this report can serve as an example for future ISAT capstone projects to integrate STS strategies into technical research procedures. And beyond that, it would be really great to see more of these approaches conducted in other departments on campus, not just ISAT. No matter the industry, the skills that have been acquired while integrating these STS procedures into this research are extremely valuable, and will continue to be used throughout the professional careers of both researchers.

5.3.2 Alexandra Treml Reflection

Through the completion of this capstone, the importance of integrating art and creativity into lab-based research has become apparent. Creating science fiction imaginations influenced the factors in systems models and allowed the researchers to envision multiple futures regarding the implementation of the technology. For example, developing a scenario analysis quadrant to understand the ramifications of a low cost, pervasive technology versus a high-cost individualized technology helps to better understand the impact of and on social status, social classes, manufacturing companies, availability of natural resources, and political acceptance. These realizations change first-hand the work in the lab from prototype to product.

Including artwork, vision boards, and role-play during STS meetings brought empathy into the materials science work. While manufacturing solar cells is mostly a predetermined process, inviting a sense of empathy into the lab creates a relationship with the scientists that is more personal, passionate, and meaningful. The team was not just creating a new solar technology; they were experimenting with potential manufacturing processes that local communities could learn as a craft to independently create energy and fuel for themselves. The future that was envisioned involved lower income communities, which were given freedom and growth with the discovery of sustainable renewable energy and fresh water.

These connections created a new and exciting synergy between the materials science work and the STS work. While the team was calculating energy efficiency and return, it was exciting to calculate the benefit of potentially creating on-shore jobs for local community members, and truly thinking about the positive (and negative) impacts of the technology and how it could change the culture, work-flow, and economy for an island community.

Regular participatory interaction and dialogue contributed to learning instead of memorizing—innovating instead of re-inventing. Although this capstone was focused on solar energy in a specific area, speaking with other members of the STS lab led to extended research on identifying and understanding stakeholders, discovering how different implementations of energy usage influence political standings, and engaging discussions on global regulations.

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